ELECTRONIC PROGRESS

RAYTHEON

in this issue:

RELIABILITY

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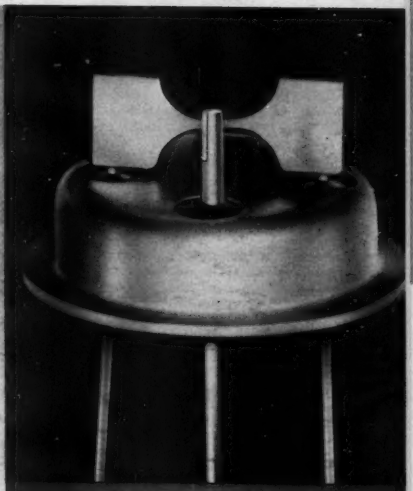

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RAYTHEON

2 Reliability—Its Meaning and Impact . . . . . *H. Elmore Blanton, E. F. Dertinger*

7 Subminiature Welds . . . . . *Charles J. Heslin*

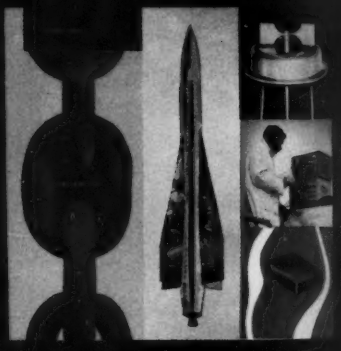
10 Profiles in Semiconductor Failure Rate vs. Application . . . . *Robert E. Pratt*

16 Reliable Systems . . . . . *Robert D. Reed*

20 Microwave and Power Tube Reliability in the Field . . . . . *A. F. Hastie*

27 Notes on Patents, Papers and Publications

Special Insert—
Fundamentals of Reliability Engineering



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A QUESTION OF RESPONSIBILITY

Nowhere in industry is product reliability more important than in the aerospace/electronics business. The occasional reader of technical literature might well question the incessant preoccupation with reliability. The trade magazine that omits reference to the term is a rarity. This issue of ELECTRONIC PROGRESS has reliability as its central theme.

Multimillion dollar space projects, compressing months of effort into one shot, have imposed fantastic reliability requirements on the designer. Modern weapon system requirements are no less stringent, since national survival might well hinge on acceptable system performance at a critical instant. All such systems, consisting of many elements working together to perform an integrated function, are no stronger than their weakest part.

Similarly, a company is a system made up of many elements, its performance no more reliable than that of any of its members. Reliable products can be produced only when each person in the organization meets his particular responsibilities for product reliability. Reliability technology has evolved certain practices to coordinate those activities that affect reliability in a major way. Control of the subtle influences is more difficult to achieve.

It is a harsh fact that product reliability can be affected by a single member of the producing chain. A $5 million system will fail in the field if a critical connection was improperly soldered or a defective part was deemed acceptable. Management installs procedures and practices to minimize such occurrences and detect them when they do occur. Such procedures cannot be completely foolproof; consequently, it remains to the individual engineer, technician, assembler, or inspector to be continuously alert. Personal diligence is a basic key to the solution of the reliability problem.

The purpose of this issue is to acquaint the reader with some of the techniques Raytheon divisions have employed in attacking particular reliability problems. If, in assessing these techniques, the reader brings into sharper focus his own responsibilities for product reliability, our efforts will have been worthwhile.

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by H. ELMORE BLANTON *and* E. F. DERTINGER

RELIABILITY

...its meaning and impact

RELIABILITY is probably the most important single word today in the electronics branch of the missile/space industry. Although reliability activities have been conducted for many years, "reliability engineering" as it is known at the present came into being about 1952. The first reliability efforts were primarily collection and analysis of field failure data, and the institution of design and process corrective actions which these analyses indicated necessary. Later, in-plant quality control activities began to be extended to include collection and "reliability analysis" of production test failure and operating time data, and feedback of recommendations to design engineering for product improvement prior to the incidence of field failures.

In the 1954-1955 era, many problems were associated with the selection and application of component parts, which were soon proven to be inadequate for the job being demanded of them. Accordingly, part failure rates and application notes and curves began to appear, with RCA's "Reliability Stress Analysis for Electronic Equipment," issued initially in 1956, becoming the basic reference document. Reliability prediction and/or estimation based upon parts counts and parts failure rates became a part of the reliability engineering activity. Reliability design reviews and paper studies came into prominence during 1956-1957 and subsequently a few test programs were initiated to check or prove the predicted reliability and to detect reasons for low reliability.

During the past eight years, military services, departments of individual services, and industry trade associations have formed reliability committees and panels to determine the general industry problems, and to recommend techniques for improving the reliability of military electronics. The Advisory Group on Reliability of Electronic Equipment (AGREE) was established by the Department of Defense in 1952 to "monitor and stimulate interest in reliability matters and recommend measures which would result in more reliable electronic equipment." The problem of increasing complexity with the accompanying decrease in reliability was recognized as becoming more and more serious. For example, the electronic equipment in Navy carrier aircraft had grown from 10 tubes in the F4F-4 (1941) to [illegible] and to 1420 tubes and 630 transistors and diodes in the A3D-2(1956); the figures for the new A3J-1 show a decrease to 430 tubes but an increase to 12,800 transistors and diodes.

As a result of the AGREE report issued in 1957, reliability specifications began to appear, very slowly prior to 1959, then in abundance during 1959-1960.

Reliability, as defined by AGREE, is "the probability of performing without failure a specified function under given conditions for a specified period of time." It is significant that reliability is expressed as a probability—thus, we have a firm, numerical basis for handling reliability in specifications, designs, and evaluations. Reliability relates to *performance without failure;* what constitutes failure, or unacceptable performance, must be clearly understood. Reliability is defined for the performance of a *specified function* under *given conditions* of environment and usage during a *specified period of time;* a change in any of these factors leads to the possibility of a different numerical value for the product reliability.

The Armed Forces are, at present, approaching the problem of unreliability in several ways:

1. Stressing the importance of improved reliability by increased emphasis in procurement requirements;
2. Developing, or sponsoring the development of, means to specify and measure reliability numerically, the key to effective contractual control of reliability;
3. Issuing specifications delineating strong reliability assurance programs for the development and production of parts, equipments, and systems;
4. Including reliability incentive clauses or reliability penalty clauses in new contracts;
5. Improving training of operating and maintenance personnel to minimize reliability problems arising from improper operation and maintenance.

Reliability will be a specified parameter for most future military products. We will have to consider it along with gain, bandwidth, speed of response, and other measures of performance during design, production, evaluation, and field application of products.

If for no other reason, reliability programs are becoming a necessity for the military, and for major companies doing military business because of the basic economic problem associated with the cost of unreliable equipment.

Economics and Equipment Reliability Levels

Operational reliability of electronics equipment depends upon four basic factors: 1) design of circuitry and packaging, 2) reliability of parts and materials utilized, 3) manufacturing workmanship, and 4) use and maintenance. Each of these factors is directly affected by the use environments, including shipping and handling, installation, and operation. Since it has been proven that reliability decreases as complexity increases, equipment reliability levels decrease with complexity and environments. The reliability levels of various types of current military electronics equipment bear out this generalization, as indicated in Figure 1.

Air Force Maintenance Costs

If several types of military electronics equipment are considered from the "economics of maintenance" viewpoint, the findings are startling. Figure 2 portrays Air Force experience with a typical ground-based radar,

*A further explanation of definitions pertinent to reliability is given in the special center insert in this issue of ELECTRONIC PROGRESS.

a navigation aid, and a UHF communications equipment. All three items are part of the Air Control and Warning System, and are operating in the North American continent ground environment.

If the achieved mean time between failures (MTBF) reliability of these three equipments could be doubled—a relatively easy task with well-planned and conducted reliability programs—the Air Force would conservatively realize savings of $850,000 over a useful life period of five years for each of these equipments, i.e., at each Early Warning Site.

Potential Satellite Costs Due to Unreliability

For satellite and space-era equipment, the importance of planned and well-conducted reliability programs becomes even more apparent. R. H. Myers of Hughes Aircraft in a recent article "Which Road to Satellite Reliability"* states that unless exceptionally high levels of reliability are achieved in satellite systems, the operation costs become prohibitive in terms of satellites needed to keep the system going, and the multi-million dollar costs per launch.

An illustration of the economics of the satellite reliability problem is given in this article in terms of a communication relay system in which four orbiting satellites are required to actively receive and transmit messages between a series of ground stations and/or aircraft. Figure 3 portrays operating costs vs. satellite reliability levels. If a 40,000-hour MTBF satellite reliability is achieved, the first-year costs for all four satellites would total $46 million, and there would be no annual replacement costs. However, if we compare the state-of-the-art figures for airborne equipment from Figure 1, it appears that a MTBF requirement of this order is ridiculous. If we achieve only a 200-hour MTBF for the satellites, which is as good as that achieved by the best airborne electronics system of this nature to date, satellite system operational costs total *$1.7 billion annually*. "One-year costs," as shown in Figure 3, reflect initial launching costs plus the cost of replacing failed satellites in order to keep the system operational for approximately five years. The dollar cost figures were derived from a) launching costs per satellite = $6 million, b) missile reliability fixed at 0.80, c) guidance reliability fixed at 0.80. This data means the probability of a satellite being successfully orbited is 0.64, a figure which is higher than our experience to date as indicated by Figure 1. Also, the cost per launch figure can easily exceed the $6 million estimate.

The $1.65 billion cost differential for this hypothetical 4-satellite system should provide sufficient justification for planning, funding, and implementing comprehensive satellite reliability programs. Actually, most current planning is for a 10-satellite system; the cost numbers must be raised for such a system by a factor of at least 2½. To further indicate the magnitude of this situation,

Annual Convention Transactions, American Society for Quality Control, 1961.

TYPE OF EQUIPMENT	GENERAL ENVIRONMENT	COMPLEXITY (Parts Count)	RELIABILITY LEVEL (MTBF) OR % SUCCESS
Radar	Airborne	1000	60-80 hours
Navigation	Airborne	1010	80-90 hours
Radar	Airborne	1350	20-25 hours
Radar	Airborne	2500	40-50 hours
Radar	Airborne	3000	30-40 hours
Radar	Airborne	9000	5-10 hours
Navigation Aid	Ground	540	300-500 hours
Comm. System (UHF)	Ground	1600	350-400 hours
Radar	Ground	2000	250-300 hours
Radar	Ground	6000	50-60 hours
Radar	Ground	7000	80-90 hours
IFF Equipment	Shipboard	475	1750-1850 hours
Navigation Aid	Shipboard	600	580-600 hours
Comm. Transceiver	Shipboard	700	475-525 hours
Navigation	Shipboard	1100	120-140 hours
Sonar	Shipboard	1300	425-450 hours
Sonar	Shipboard	3000	140-150 hours
Radar	Shipboard	9000	5-10 hours
Missiles	Ground and Air	200-1000	90-98%
Missiles	Ground and Air	1000-3000	70-93%
Missile-Satellite Launchings	Ground and Air	10-50,000	58% over-all average

Figure 1. Reliability levels vs. complexity and environment

and to prove that we must conduct effective reliability programs for sheer economic reasons if for no other purpose, consider the total number of missile and space programs under way in one form or another. The March 6, 1961 *Missiles and Rockets*, "ASTROLOG" lists 113 missile and space programs. In this same issue, in a story entitled "NASA Reveals Price Tags," the cost of developing and producing the first nine SCOUT vehicles is stated to be $17 million, with $935,000 indicated as the cost of each launching. For CENTAUR, $170 to $180 million will be spent for developing and producing the first 10 vehicles, with $20 million for each launch. With such huge expenditures, there can be no alternative for NASA but to enforce meaningful reliability programs, such that there is a high probability of successful launch on each attempt to put a space vehicle in orbit, and a corresponding high probability of continued electronics equipment operation once in orbit.

Component Parts Reliability and Maintenance Costs

Component parts reliability is one of the major problems confronting us in regard to achievement of higher operational reliability levels for current equipment, and it is the key to satisfactory reliability for space-era equipment.

Improved parts will be made available as a result of such direct efforts as the Minuteman and Titan II parts improvement programs; a similar program is planned for Midas. Paralleling these "parts improvement program" efforts, the Department of Defense Ad Hoc Study Group on Parts Specification Manage-

ment for Reliability is attempting to upgrade the reliability levels of all military electronic parts.

To understand why such efforts are vital to improved electronic equipment reliability, let's assume that 1 billion electronic component parts are utilized in our total current inventory of military electronics equipment. Further, let's utilize an RADC estimate of $20.00 per part replacement, and develop five-year maintenance costs, as a result of various levels of parts reliability. Both figures are very conservative.

For this analysis, an average, current state-of-the-art component part failure rate of 0.2 percent per 1000 hours is used as our base. (This is actually better than that achieved for most Mil-Standard parts.) Figure 4 indicates the 1000-hour, 5000-hour, and 40,000-hour maintenance costs for equipments using parts of this reliability level. For improved parts of the order of 0.1 percent per 1000 hours, and for high-reliability parts of the order of 0.01 percent and 0.001 percent per 1000 hours, the resultant reduced maintenance costs are indicated. The 0.001 percent application-use failure rate is approximately that being sought for Minuteman component parts.

TYPE OF EQUIPMENT	ORIGINAL COST	ACHIEVED MTBF	(ANNUAL) MAINTENANCE COST
Radar	$400,000	55 hours	$240,000
Communications	6,000	390 hours	70,000
Navigation	5,000	337 hours	29,000

Figure 2. Maintenance cost vs. original equipment cost

From Figure 4, it becomes apparent that tremendous savings could be realized through development and production of high-reliability parts. For normal equipments, at least $100 million per year could be saved, and this is a conservative estimate for reasons previously stated. For space-era equipments, billions of dollars could be saved each year.

Reliability at Raytheon

Raytheon has compiled an enviable record as a supplier of products of high quality and reliability. This record, as reflected by such products as the Hawk and Sparrow missile systems, radars and guidance equipment of various types, reliable subminiature tubes, and semiconductor devices, is the result of careful and continuing management emphasis on all phases of reliability and quality control. Partially as a result of this record of achievement, the Company is currently engaged in a variety of programs having high-reliability requirements, for example, the Mauler missile guidance system, the Polaris guidance computer, the Pincushion radar, and transistors for the SAC world-wide communications system.

Raytheon upholds the policy that its products shall be delivered to customers on schedule at a competitive price, and that they shall meet all specified and implied

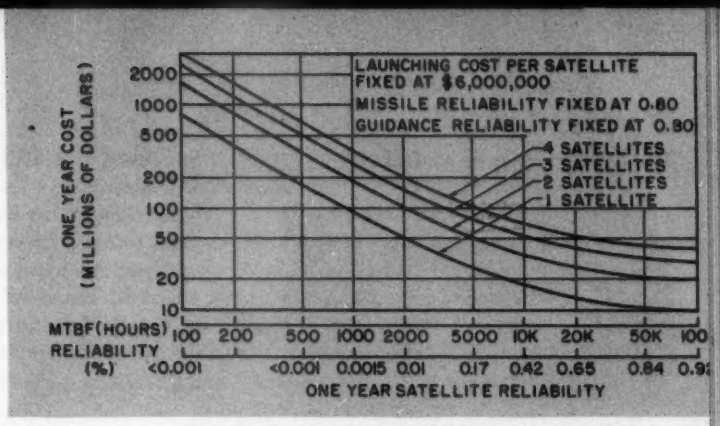


Figure 3. Operating costs vs. satellite reliability levels

standards of performance, quality, and reliability. It may be noted that equal emphasis is placed on the triad—performance, quality, and reliability. The statement of this policy is amplified by the Raytheon Engineering and Quality Control manuals, and related documents, which provide detailed instructions for guidance and assistance.

The basic responsibility for the fulfilment of this policy rests directly with the engineering and production personnel and their respective managers. Strong support, assistance, and control are provided by specialists having specific reliability and quality control responsibilities.

To implement this policy, Divisions generally follow the *product assurance concept*, which stresses that a product shall meet all customer requirements. This concept is applied in varying ways in the different Divisions according to the needs of their product lines. Coordination of related activities in the several Divisions and assistance on common problems are provided by corporate staff specialists. The application of this concept results in the establishment of means for ensuring that the combined talents of the reliability and quality specialists, as well as those of specialists in value, producibility, maintainability, and similar areas, are brought to bear on common problems in a coordinated manner. Such action assures that appropriate balance is achieved between performance, reliability, quality, and cost throughout the engineering and production cycle.

The product assurance approach to reliability has evolved from Raytheon experience through the years. The formal organization of reliability specialists dates to approximately 1955. In that year, the Missile Systems Division formed a reliability section in its Bedford Laboratory, grouping together personnel whose earlier efforts had contributed to the high degree of reliability designed into the Sparrow III missile. At about the same time, the Equipment Division formed a reliability committee to investigate improvements needed in part selection, testing, and inspection and quality control procedures to ensure product performance. This committee's findings led to the formation of reliability sections at the Division's Maynard and

Wayland Laboratories during 1957, and formalization of the Division's product assurance concept in 1958. The presence of these groups in the Company's systems development areas has contributed significantly to the proven reliability of the large systems being produced by Raytheon today—the Hawk and Sparrow missiles; the high-speed bombing radars for the B-52; the search, bombing, and navigation radars for the B-58 aircraft; the WSR-1 weather radar; the ARSR air traffic control systems; and the large surface search radars, FPS-19, FPS-28, SPS-38, and SPG-51.

While the systems divisions were becoming better organized to cope with reliability problems, the Company's component-producing divisions were no less active in the field.

The Microwave and Power Tube Division began in 1955 a program to effect needed improvements in magnetron reliability. This program is particularly significant because it gave careful study not only to causes originating during engineering and manufacturing, but also to those associated with transportation, field application, and other stages of the product life cycle. The significant improvements that have been recorded—for example, increases by factors of four to eight in the *average* field operational life of several types of tubes—have reemphasized the importance of a fully coordinated product assurance approach where appropriate attention is given to all potential quality/reliability problems from the time of the inception of a product until the product must be discarded because of justifiable causes of wearout or failure.

The Special Tube Division (now a part of the Industrial Components Division) early tackled the problem of unreliability in miniature and subminiature tubes. This work led to the offering of a product line known as "RELIABLE Subminiature Tubes." To qualify for this designation, the tubes were designed and constructed so that they would withstand stringent environmental and life tests. Other precautions, such as 100 percent microscopic inspection, were taken to ensure extremely high reliability (by existing standards) during usage. The success of this effort is evidenced by the adoption of these tubes for use in a large number of ballistic and anti-aircraft missiles. More recent efforts in the Industrial Components Division have been directed towards further improvement in tube reliability, and the realization of a high degree of service reliability in welded, transistorized modules, which are being used with great effectiveness in a variety of applications, including the Polaris Mark 2 Guidance System.

The Semiconductor Division's reliability assurance program started in its present form about two years ago. A key element is a continuing load-life test program, employing sample sizes sufficiently large, and test conditions adequately realistic, to ensure that the resulting failure data are valid to a high confidence level. The data from this test program, besides providing information useful in achieving further product improvement, serve to demonstrate positively to our customers that current production is yielding a product of uniformly low failure rate.

Looking Ahead

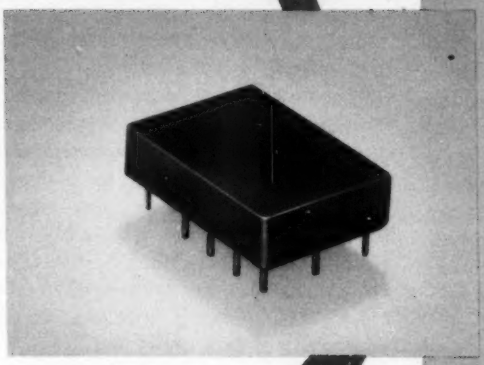
From the data provided regarding future product costs and requirements, it is apparent that drastic changes must take place relative to design, production, and maintenance of military electronics equipment. This is a story we have all heard for years. Today, however, we are in a better position to cope with the problem We now know how to establish meaningful reliability programs, and the military customers are going to insist upon such programs for all major contracts in the future. They have good specifications and intend to enforce them; more than 600 contracts under way at this date include such specifications. NASA has stated an intention to go beyond the requirements of the present reliability specifications including use of technical monitoring agencies to enforce reliability program requirements; at least two such programs are already under way. By 1965, the three services and NASA will be devoting the major portion of their budgets to missile/space/astronautic programs, the type of electronic equipment which demands high inherent reliability.

In conclusion, a quote from the February 27, 1961 *Missiles and Rockets* Editorial seems quite appropriate: "We are all getting a little tired of the word reliability—*but it is probably the most important single word today in the electronics branch of the missile/space industry* . . . No matter how tired of it you get, it is with us to stay and you'll hear it on Mars."■

PART RELIABILITY (FAILURE RATE IN %/1000 HOURS)	FAILURES PER BILLION PARTS PER 1000 HOURS	MAINTENANCE COSTS*		
		1000 HOURS OF OPERATION	5000 HOURS OF OPERATION	40,000 HOURS OF OPERATION
0.2	2,000,000	$40,000,000	$200,000,000	$1,600,000,000
0.1	1,000,000	20,000,000	100,000,000	800,000,000
0.01	100,000	2,000,000	10,000,000	80,000,000
0.001	10,000	200,000	1,000,000	8,000,000

*Based on Average Part Replacement Cost = $20

Figure 4. Maintenance costs as a function of total parts used and parts failure rates



SUBMINIATUREWELDS

by CHARLES J. HESLIN

The diversity of products manufactured by the Industrial Components Division, including the development of compact Welded Modules for use in missiles, satellites and other space age equipments created the need for an extensive reliability program for each product. One program on one process will be examined to illustrate a typical reliability effort.

Since the number of welds in one type of modularized computer would approximate 23,000, the reliability of the welding process was immediately analyzed. All available data was gathered including our history on welding of reliable tubes. Data on weld reliability shows:

TEST	MTBF (JOINT HOURS)
10,000 hours operating life test— 230 vacuum tubes, 15 welds per tube	35,000,000
1,000 hours operating life test— 3,000 vacuum tubes, 15 welds per tube	45,000,000
Welded module life test —two design model computers have completed 19,000 hours and 5,000 hours, respectively, with one failure	552,000,000

In addition to the above, records of vibration and shock test for the last two years (1959-60) were examined and showed:

Vibration test sweep frequency of 5-2000 cps at 10g and 6 hours duration with the tube operating	0 failures in 59,000 joint hours
Vibration test, 25 cps, 2½g— 96 hours duration with the tube operating	0 failures in 3,900,000 joint hours
Shock test, ½ sine wave, 450g, 0.75msec	0 failures in 44,000 joints tested

To be certain that welded modules would make a significant contribution to equipment reliability as well as effect important reductions in the size and weight of equipments, it was decided to compare the reliability of welded connections with soldered connections.

Data on solder joints obtained from various technical publications indicated a MTBF of approximately 50,000 to 2,000,000 hours. The best reliability figures, 20,000,000 hours MTBF and 100,000,000 hours MTBF were found in the forms of present and future goals to be achieved. It was apparent that weld reliability had already exceeded this solder joint reliability goal. Figure 1 graphically compares the MTBF for welded and soldered connections on computer joints.

A review of future reliability goals for missiles and space age systems indicated a major effort should be expended to further improve current welding capabilities. The program established to achieve the highest possible weld reliability took many avenues of approach.

The first step in the program was to determine a method for distinguishing between marginal and satisfactory welds. Many methods were investigated including resistance measurements, visual inspection, X-Ray inspection, metallurgical examinations, and various physical destruction methods. A simple destructive test using a tensile tester to stress the weld in the worst combination of tension, shear, and torsional stress was established as the standard to use for future experiments. Metallographic examinations and visual inspections were used to aid in analyzing the results of the tests.

Before progress could be made, it was necessary to determine the variables affecting the integrity of a weld and to develop means of measuring the variables.

The variables which had the greatest effect on weld quality and strength were: 1) pressure applied as a function of time, 2) instantaneous peak power, 3) energy dissipation, and 4) the time duration of the weld cycle. A gauge for measuring applied electrode pressure had been developed and was in use. Therefore, a measuring device or method had to be developed which would give an accurate picture of the other variables.

During the weld cycle, conditions are varying constantly, making measurements of these variables extremely difficult. To solve this problem, a method was developed to measure the variables at the electrode tips under simulated weld conditions and then measure the effect at these conditions on actual welds. These initial studies led to the development of a simplified device which could be used in production to set up quickly and accurately the desired operating conditions on the weld equipment.

Isolation of, and removal or control of the variables in the welding equipment affecting the inputs to the weld was a major objective. Figure 2 shows the resistance variables in the welding head that could cause variations in weld strength. Investigation of these variables uncovered many items affecting weld uniformity. Some of these items were differences in clamping pressure, different configurations of connecting cables and lugs, and differences in surface finishes on contacting surfaces. Tests were also run on line voltage fluctuations, power supply repeatability, and transformer capacitance effects. Parallel efforts were made on the uniformity of force applied and electrode alignment. This work led to immediate improvements in welding techniques and pointed up the need to develop an improved welding head.

The next problem was to determine the most effective combinations of welding equipment, electrode size, shape and material, and applied energy and pressure to optimize weld strengths for particular material combinations. As a starting point a matrix was made of all the combinations that were to be studied. From this matrix the order of importance and time table for accomplishment was developed. In order to analyze the results of our tests quickly and accurately the 90 percent isostrength chart was devised.

Typical charts are depicted in Figures 3 and 4. The ordinate of the chart is in pounds of force applied and the abscissa is in available energy in watt-seconds. Each isoline on the chart indicates a breaking strength that 90 percent of the welds should exceed when made at the particular force and energy settings. The chart is prepared by:

1. Making welds at each setting combination
2. Testing the welds
3. Plotting the results on probability paper to determine the 90 percent point
4. Plotting the points on the chart
5. Joining the points of equal breaking strength.

Isostrength charts not only compare optimum strengths but also the extent of the margin of safety at the particular settings. They also take into account dispersion of weld strengths as well as average weld strength and allow quick comparison with other tests. A comparison of Figures 3 and 4 portrays the above points. The only difference between the two tests shown in the charts was a change in material of the top electrode. The maximum isostrength line was 15 pounds in one test and 13 pounds in the other test; the higher

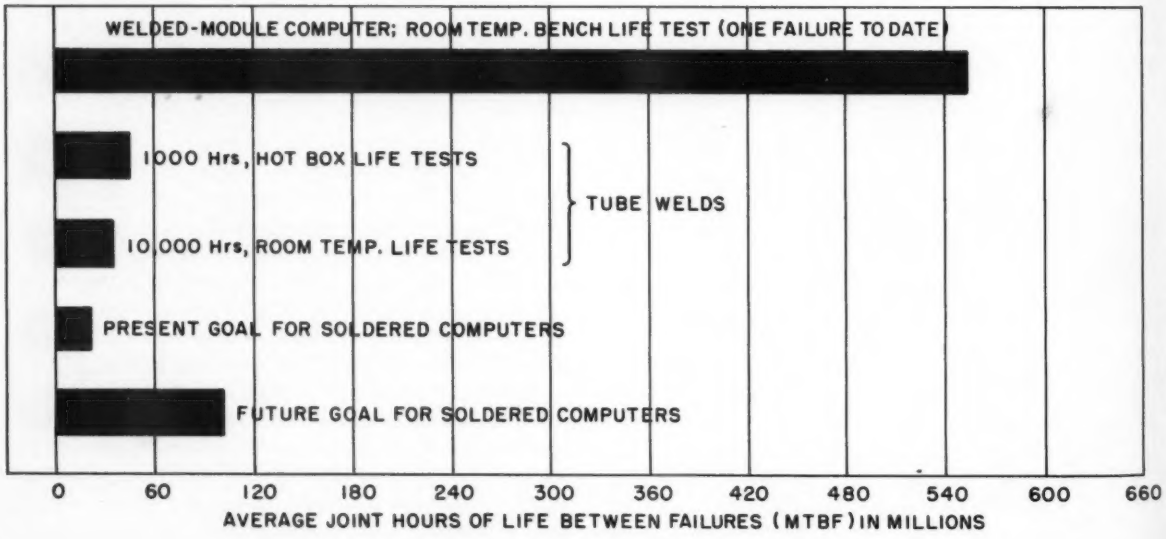


Figure 1. Comparison of estimated MTBF on computer joints

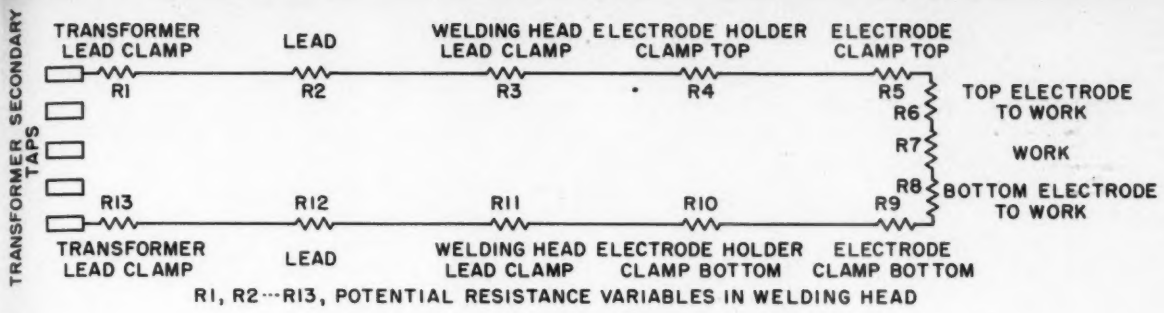


Figure 2. Resistance variations in model "J" head welder

strength test providing wider margin of safe operation. In addition to selecting the best combinations of equipments, programming, and establishing controls, this investigation brought about changes in component lead materials used in products. Lead materials that would give the highest uniformity and a high weld strength were selected and incorporated in design wherever improvements could be realized.

A great deal of thought, planning, and attention goes into the establishment of controls on materials, processes, equipment, and testing. To assure that incoming component lead material is of consistent quality each lot of components is spectrographically analyzed, physically measured and functionaly tested for its weldability. The weldability test is made by cutting samples off the component leads and welding them to the same type of material to which they will be joined. The welds are made at the established setup and must meet the specified limits for breaking strength established by previous reliability studies.

Process control is enhanced by:

1. Having specified welding setups for each combination of material to be welded,
2. A well-established routine of preventive maintenance and periodic equipment calibration,
3. A strong setup inspection at each welding station that must be passed before starting the process.

The setup inspection is accomplished in the same manner as the incoming weldability test. This method assures that the setup is made on exactly the same materials that will eventually be joined.

The quality of the welding process is further assured by the careful placement of in-process inspection and test stations throughout the manufacturing cycle.

Many other items were included in the over-all reliability program on welding. Some of these items were:

1. The training of operators and inspectors,
2. Evaluation of the effects of surface preparation and physical properties of materials on weld strength,
3. Material handling procedures,
4. The development of special jigs and fixtures to improve the welding or testing operation.

Improvements are being made daily that increase welding reliability and it is firmly believed that ideas now being pursued eventually will lead to equipment that will not only make a weld but will also tell us the quality of the weld it made.

The intensive investigations to date have led to a clearer understanding of the variables involved in making reliable subminiature welds. The new knowledge acquired, coupled with our extensive welding experience on tubes, has already resulted in practical improvements in equipment, methods of testing, and controls.■

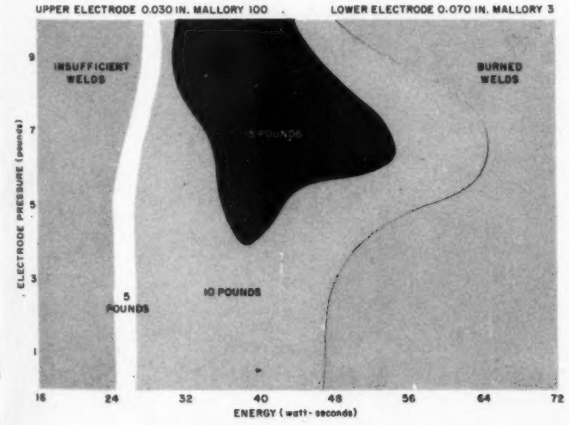


Figure 3. Isostrength chart

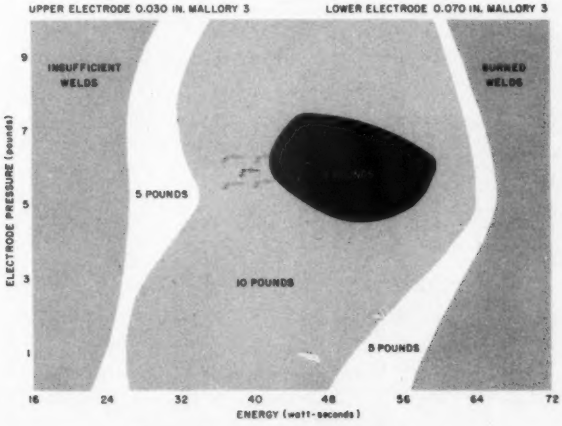
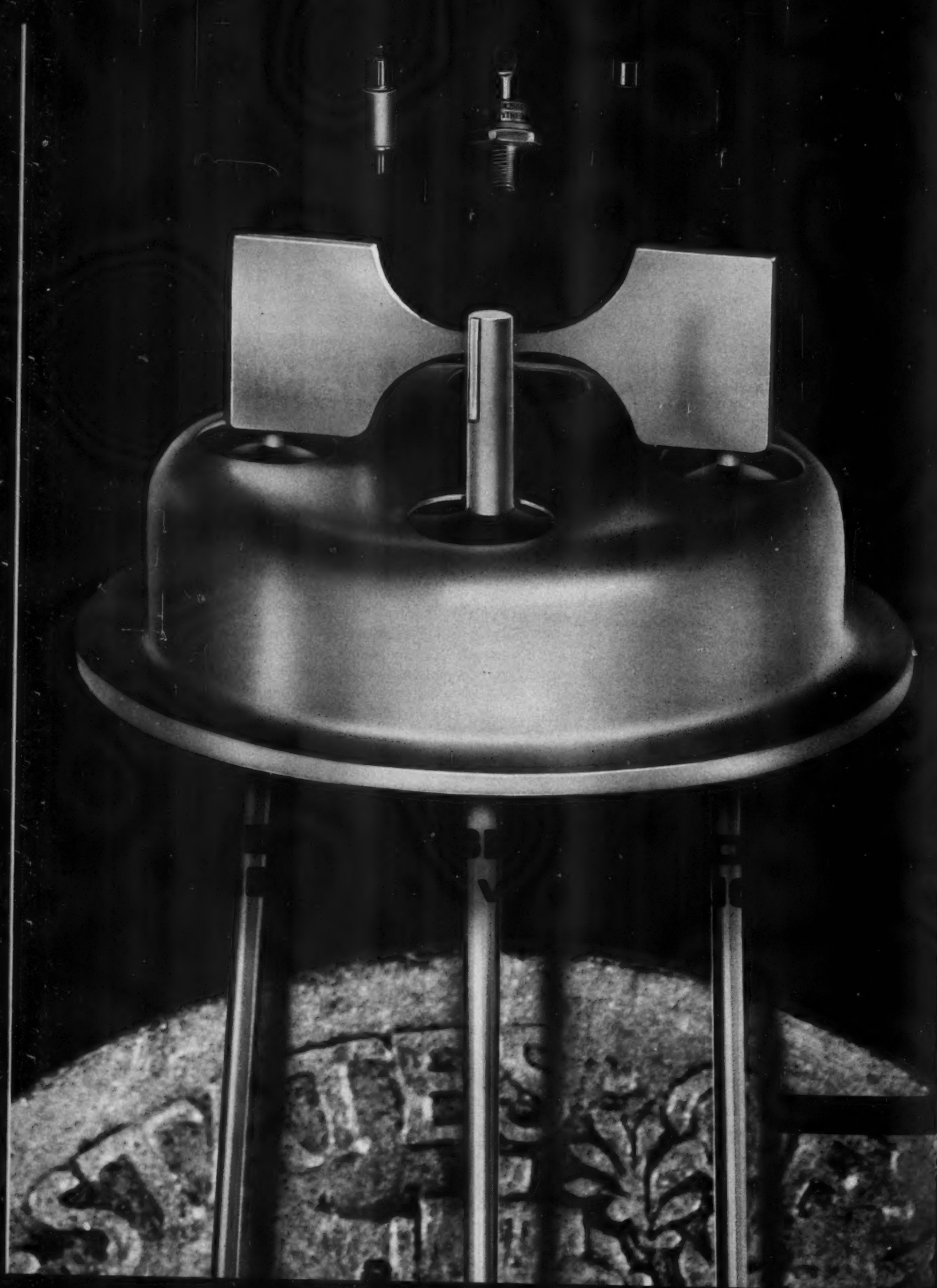


Figure 4. Isostrength chart

(0.025 in. 42 alloy welded to 0.010 in. x 0.030 in. nickel)



FAILURE RATE information has been scarce and sketchy in the semiconductor device field. Lot acceptance life test information is inadequate for many circuit design problems where a designer is faced with meeting certain reliability requirements. In this paper a method is described for analyzing and presenting life test data in a manner which will be useful to circuit designers. While the curves and numbers used in this report are hypothetical, they closely approximate actual experience. These methods are now being used and the results are being published as the analyses are completed.

The needs of equipment manufacturers for numeric reliability information are being felt by device manufacturers. In order to predict equipment reliability, the associated reliability of component parts must be known under the equipment use conditions. Not only must there be knowledge of the numerical values involved, but the assumptions and risks involved in obtaining these values must be understood.

Raytheon's Semiconductor Division is operating a reliability assurance program on all of its products as an economical, yet highly effective, method of providing dependable performance and reliability design information. This is in addition to the many military and customer qualification and lot acceptance life tests. The assurance program is operated on a family-by-family basis; i.e., the production line producing a parent family is sampled daily or weekly depending on sample size. Samples are placed on life test in the real-time domain so there is a continuous stream of any individual family completing 1000-hour life test.

The data generated, as well as the devices which do fail are returned to product engineering to provide information for product improvement. In this manner each production line is under continuous surveillance. Product design, manufacturing processes, and purchased materials are always being monitored in terms of their effects on the devices. In this way, the information feedback loop is closed in a controlled, continuous, fast, and effective system.

Historically, most reporting of life test results has typically consisted of stating that 1 unit out of 50 has failed the specified end-points after 1000 hours of life test at some known conditions. More recently, graphs have been published showing the average, 5 percent, and 95 percent values of a parameter throughout a life test.

However, as products improve it serves no useful purpose to peruse graphs of this type. It is doubtful that this information helps a designer meet specific requirements. This is especially true when such items as cost, weight, size, and complexity are other factors for which he is held accountable. It is even more doubtful that statistically the information presented is much more meaningful than estimating the results. The problem appears to be the attempt being made by some to obtain design engineering information from lot acceptance life test data. What is actually needed is a life test program that is specifically designed to obtain engineering information. It is interesting to know the failure rate for a specific set of conditions and end points, but it is more important to the designer to know how failure rates vary as the life condition and the definition of a failure are varied.

The life test program should answer these questions:

1. How important is derating junction temperature?
2. Is it more valuable to derate breakdown voltage 20% or leakage current 100%?
3. How much increase in reliability can be expected if design end-of-life for H_{FE} is changed from 90% of initial lower limit to 70%?
4. If designing wider end-of-life tolerance is necessary, which characteristic will produce the largest improvement for the least redesign work?
5. Do storage and operating life tests give compatible results?

The only way to answer these questions is to place sufficiently large quantities of devices on life test to generate enough failures at each of the test conditions to be able to draw statistically significant conclusions from the data. As the over-all reliability improves, however, this becomes more and more difficult.

A failure to a circuit designer is only a failure if the component will not satisfactorily perform in the application. When does it cease to perform satisfactorily? This varies, since some circuits are more critical than others. It is not realistic, therefore, to use reliability figures based on one design derating factor to predict the reliability of two circuits that fail at different degradation levels. What is needed is a technique of presenting life test results in such a manner that the circuit designer can relate his particular design to the life experience developed on the life test. For example,

TABLE I

LIFE TEST REQUIREMENTS
MIL-T-19500/44A

TEST	CONDITIONS	AQL (%)	INSP. LEVEL	SYMBOL	LIMITS min	LIMITS max	UNIT
SUBGROUP 1 STORAGE LIFE	T_A = 85°C, 1000 hrs	4.0	L5				
SUBGROUP 2 OPERATING LIFE	V_{CB} = −15 Vdc I_C = −3mÅdc T_A = 65±2°C 1000 hrs	4.0	L5				
LIFE TEST END POINTS 1000 hrs COLLECTOR CUTOFF CURRENT EMITTER OPEN	V_{CB} = −30 Vdc			I_{CBO}		40	μÅdc
EMITTER CUTOFF CURRENT 1 COLLECTOR OPEN	V_{CB} = −20 Vdc			I_{EBO}		40	μÅdc
DC CURRENT GAIN 1	I_B = −1.0mÅdc V_{CE} = −0.25 Vdc			H_{FE1}			

the designer has chosen Mil type 2N428, Mil-T-19500/44A transistor. The life test requirements in this specification are summarized in Table I.

The particular circuit that the designer is evaluating relies on two characteristics to perform satisfactorily: I_{CBO} at $V_{CB} = -12$ volts, and DC current gain. In addition, units may experience high collector voltage during servicing or abnormal operation of the system. These characteristics, the measuring conditions, the initial purchase specification limits, and the circuit malfunction values are shown in Table II.

TABLE II

INITIAL SPECIFICATION REQUIREMENTS AND CIRCUIT MALFUNCTION LIMITS

CHARACTERISTIC	CONDITION	INITIAL LIMIT	CIRCUIT LIMIT
I_{CBO}	$V_{CB} = -12$ Vdc	6 μA max	10 μA max
H_{FE}	$V_{CE} = 0.25$ Vdc $I_B = 1$ mA	60 min	48 min
BV_{CBO}	$I_C = 25$ μA	30 V min	24 V min

Material purchased to Mil-T-19500/44A is required to meet a 4 percent AQL for life test requirements. It is understood that a manufacturer must produce a product with a process average percent defective equal to or better than the AQL in order to economically produce the devices. Suppose the designer learns from the vendor that the last 6 lots submitted for Mil Lot Acceptance passed. This Mil Lot Acceptance data might appear as in Table III.

TABLE III

HYPOTHETICAL MIL LOT ACCEPTANCE DATA

LOT NO.	OPERATING		STORAGE	
	UNITS ON TEST	DEFECTIVES	UNITS ON TEST	DEFECTIVES
1	35	0	35	0
2	15	0	15	0
3	25	1	25	0
4	25	0	25	1
5	35	1	35	0
6	35	0	35	0
TOTALS	170	2	170	1

All 6 lots would pass with flying colors. The combined process average failure rate would be $3/340 = 0.9$ percent per 1000 hours.

The process average offers very little in the way of information for the designer. Several problems exist:

1. I_{CBO} at a voltage below breakdown is not end-pointed.
2. Breakdown is end-pointed at 30 volts, but circuit will not fail until end-point of 24 volts is reached. Even if variables data is available from the vendor, it is of very little use since the specification calls for reading the leakage current at 30 volts.
3. The specification end-points gain with a larger degradation allowance than the circuit can stand. The designer needs to know the reliability in the circuit in order to decide whether another stage is required to meet the reliability goals.
4. The specification involves an emitter high voltage leakage end-point. The circuit in question does not fail for emitter leakage or emitter breakdown since the emitter base diode is never reverse biased.

This indicates that information pertinent to circuit design may not be obtainable from lot acceptance life test data. Where then should this information be generated? The device manufacturer is the logical source. If he is conscientiously attempting to produce high reliability devices, he needs this same kind of information along with the actual life test failed units in order to direct his product improvement efforts. Since life test information cannot be made available at every conceivable operating condition to all possible end-points, a practical approach to obtaining useful design information at an economically justifiable cost is needed.

Semiconductor devices are not presently being produced type by type. A generic family of devices provide the source from which various types are selected. It would seem that a program to determine the reliability of the generic family would provide an adequate description of the reliability of types extracted from the family. Checks must be continually made to be sure that this assumption is valid (i.e., tests to determine that failures are distributed randomly from the production population).

The recording of variables data on large quantities of devices becomes practical with the availability of high-speed digital test equipment. If the recording is done in the form of punched cards, it is practical to perform a variables, or quasi-variables, analysis on huge masses of data. For failure rate analysis, it is only necessary to analyze the variables data on units exceeding initial characteristic limits. This card processing has been programmed on an IBM 101 statistical machine. Once the data for all devices is reduced to that portion which exceeds one or more of the initial specification limits, analysis beyond this point can be performed manually. All that has been developed so far is the failure rate if no degradation from initial specifications is allowed. This data can be analyzed further using the variables characteristic of the data itself to generate the engineering information. These out-of-tolerance units can be segregated into cause of failure according to these categories:

1. *Catastrophics*—shorts, opens, units whose parameters have changed so much that few designers would compensate for these deviations.
2. *Collector Junction*—any unit exceeding initial I_{CBO} limit or whose BV_{CBO} is less than the initial limit.

3. *Emitter Junction*—any unit exceeding initial I_{EBO} limit or whose BV_{EBO} is less than the initial limit.
4. *Forward Current Gain*—special provisions must be made here where a full production family of products is placed on life test. One possible method is to initially classify units into classes, then record data on units dropping out of class.

At this point it is possible to determine which of the categories contributes heaviest to the over-all out-of-tolerance picture. Analysis of each of these categories can be fruitful both in determining product improvement steps and circuit design information.

First, a more precise definition of a catastrophic failure is required. Shorts and opens are obvious. Collector and emitter junction criteria, however, can be somewhat arbitrary and will depend to a large extent upon the instrumentation used and the possible interactions of the leakage and breakdown test condition. The choice of catastrophic limits at the point of coincidence between the test conditions and limits for the two tests has been chosen for the analyses performed to date.

Analysis of the units classified as catastrophic failures should be made to determine that one problem is not contributing heavily to the catastrophic failure rate observed. Catastrophic failure rates of the order of 0.1 percent per 1000 hours have been observed.

A more explicit definition of a collector junction failure is also necessary. Two characteristics of the collector—leakage current and breakdown voltage—can be called out-of-tolerance for this category. Units may fail for either or both of these characteristics. Care must be exercised in developing a technique that will not count as two failures a unit that fails both characteristics. This would give an artificially high failure rate. The technique used here is to plot the 1000-hour values of BV_{CBO} and I_{CBO} of each of the out-of-tolerance units. The values are converted to percent of the initial specification limit. An example of what this might look like is shown in Figure 1. It can be seen that there are four distinct logical areas on this plot:

Area 1: (No points shown) where all units met initial collector characteristics at 1000 hours.

Area 2: Units plotted in this area fell outside initial specification limits for BV_{CBO} but met initial specifications limits for I_{CBO}.

Area 3: Units plotted in this area fell outside initial specifications for both BV_{EBO} and I_{EBO}. These are the interaction failures.

Area 4: Units plotted in this area fell outside initial specifications limits for I_{CBO} but met specification limits for BV_{CBO}.

The failure rate of the collector junction for any set of circuit end-points may be determined by masking

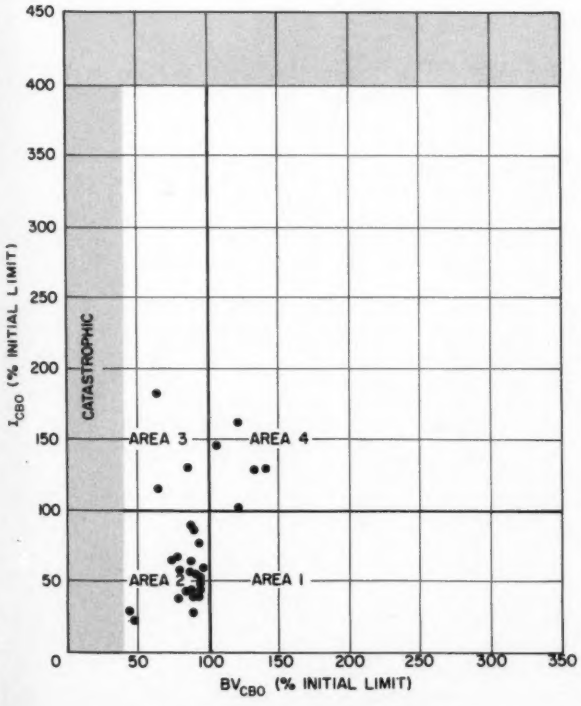


Figure 1. Collector out-of-tolerance units

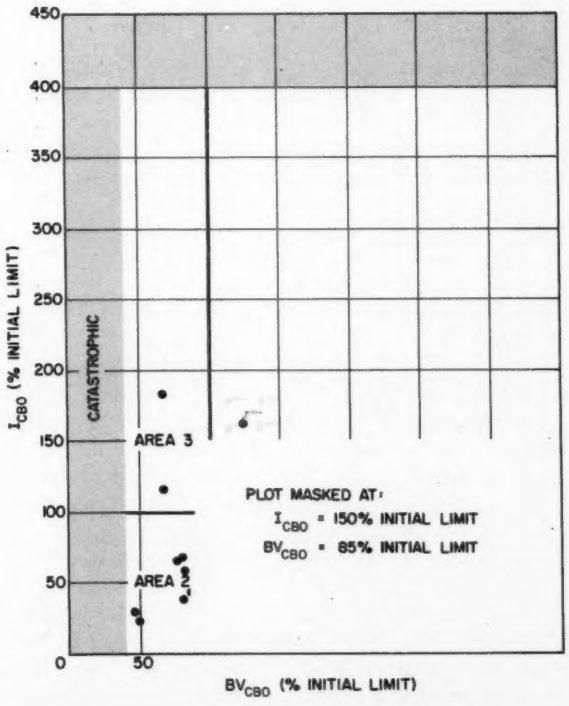


Figure 2. Illustration of selective masking

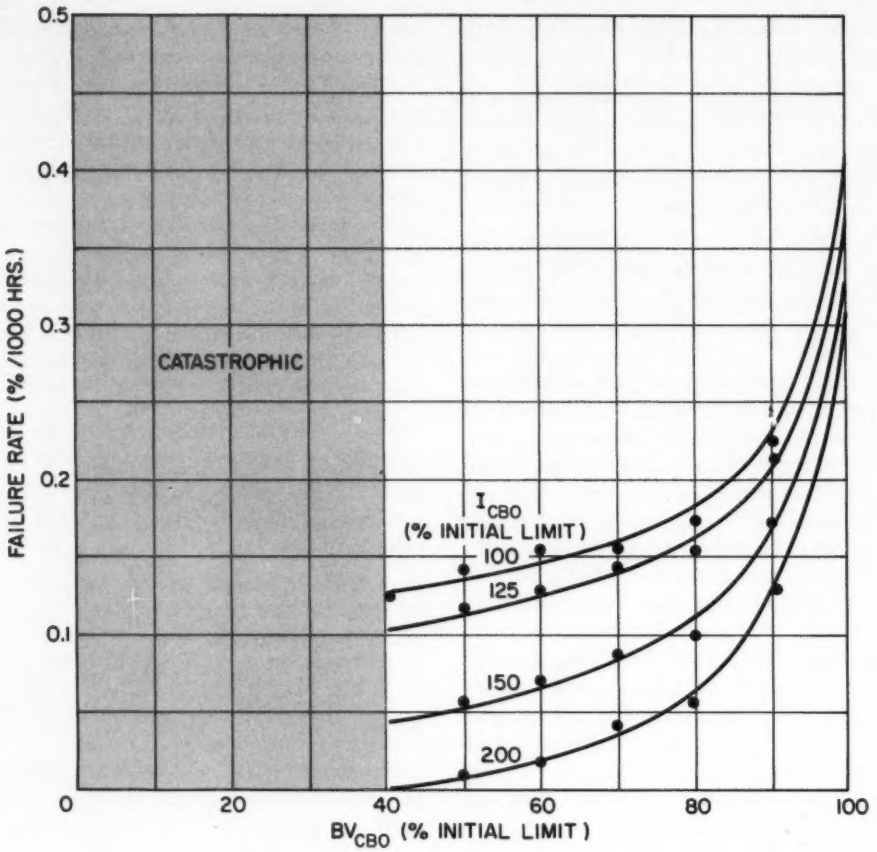


Figure 3. Constant I_{CBO} limit contours

this plot with a piece of paper lined up on the circuit end-points as a percentage of the initial purchase specification, counting the remaining points, and dividing by the total number of units on test. This is illustrated in Figure 2. This is a tedious and time-consuming method and does not impart a feel for how the failure rate changes as a function of changing circuit end-points.

Figure 3 illustrates successive application of the above techniques at finite steps of I_{CBO} end-points. Figure 4 represents a further reorganization of the data to show the constant failure rate contours. From this type of presentation, it is possible to see the relative value of derating BV_{CBO} and I_{CBO}. Notice that the curves for this particular example are somewhat hyperbolic in shape, suggesting that there is an optimum relationship between the BV_{CBO} and I_{CBO} derating.

The third cause of failure, emitter junction, can be analyzed in a manner similar to the collector junction analysis.

Finally, a further explanation of forward current gain is necessary. The engineering information necessary for optimum design is difficult to obtain from a program that is life-testing products on a production family concept. For many applications, gain decreasing is far more detrimental to circuit performance than gain increasing. In fact, many circuit designs are based on certain end-of-life lower limits and little or no attention need be paid to the upper limit. The approach used in analyzing data for this parameter is as follows:

1. Units are originally classified into gain categories 20 units wide.
2. The data is further analyzed on any unit in which the gain decreased sufficiently to drop it out of its original classification.
3. For each out-of-tolerance unit the 1000-hour reading is computed as a percentage of the lower class limit of the zero-hour gain classification.
4. These cards are arranged in increasing percentage values.
5. Cumulative percent failure rate curves are plotted as a function of the percent of initial lower class limit.

An example of what this curve might look like is shown in Figure 5. It must be remembered that this is based on an original gain classification 20 units wide. If the initial purchase specification is greater than 20 units wide, the failure rate may be estimated using an approxima-

continued on page 15

FUNDAMENTALS OF RELIABILITY ENGINEERING

RAYTHEON

This special insert presents brief synopses of several fundamental techniques useful in achieving reliable products. The pages may be easily removed from the magazine and punched for filing in reference notebooks. Further information may be obtained by contacting local reliability or quality managers or by calling the Company Reliability Engineering Manager, Executive Offices, Lexington (X243). Some of the material presented herein has been adapted from a series of Reliability Bulletins issued by the Reliability Engineering Section, Wayland Laboratory, Equipment Division.

Definitions

The following definitions of key terms in reliability engineering are drawn largely from the recently issued MIL-STD-721 (Navy) entitled "Definitions for Reliability Engineering." Slightly different definitions may be more useful, depending on a particular product. Although reliability relates to the *non-failure* of a product, it is convenient to define it relative to *failure;* hence the emphasis on *failure* in this list.

Failure: The inability of a system, sub-system, component, or part to perform its required function.

Failure Rate (λ): The number of failures per unit time.

Early Failure Period: That period of time following initial operation during which failure occurs at a higher than normal rate. (This period is often called the "debugging period." See Figure 1.)

Normal Failure Period: That period of time during which the failure rate remains essentially constant. (If "debugging" has eliminated all significant design defects and unsound parts, principally *chance* or *random* failures will occur during this period. Individual random failures cannot be predicted, although statistics often may be used to describe their probable frequency of occurrence. Reliable electronic equipment has been shown to exhibit a relatively long normal failure period.)

Wearout Failure Period: That period of time after the normal failure period during which the equipment failure rate increases above the normal rate. (This increase is due to excessive degradation or wearout of parts. Since degradation or wearout are usually predictable, the start of the wearout failure period often can be delayed by a planned program for the replacement of degraded parts.)

Mean Time Between Failures (MTBF or θ): The mean operating time betwen failures during which time the item performs as specified. (For electronic equipment this measurement is usually made during the Normal Failure Period, for which case the failure rate is essentially constant and $\theta = 1/\lambda$.)

Reliability (R or P): The probability that a system, sub-system, component or part will:

a. perform its intended function
b. for a specified period of time
c. under stated conditions.

(For most electronic equipment, the reliability during the Normal Failure Period may be represented by $P = e^{-t/\theta} = e^{-t\lambda}$, where time t is measured from the start of the specified period of operation. See Figure 2.)

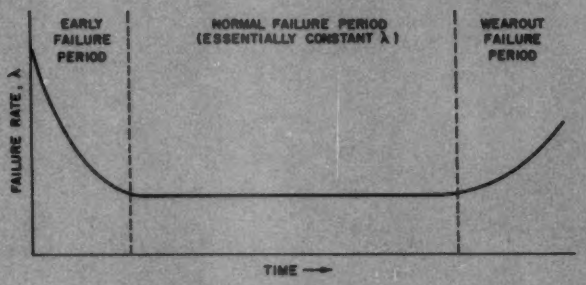


Figure 1. Typical failure pattern

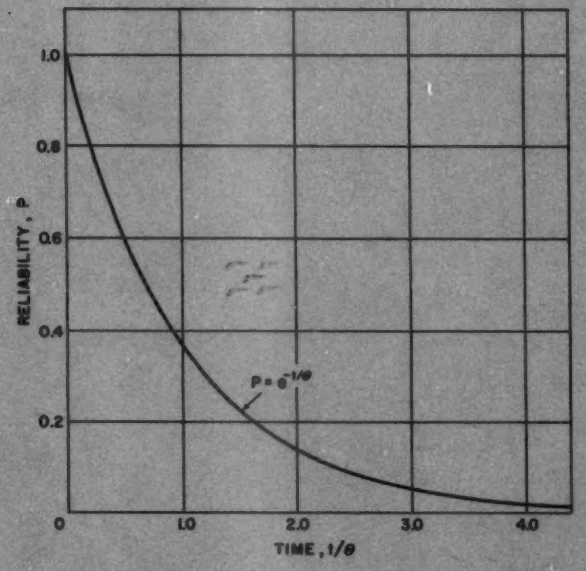


Figure 2. Exponential reliability function

Calculation of Reliability

The reliability of a system depends on the reliability of its constituent sub-systems, components, and parts. During system design it is often desirable, or necessary, to predict reliability or to estimate the improvements in inherent reliability resulting from various design changes. Calculation of system reliability from data describing the components depends on how the components combine. That is, component reliabilities can combine in series; when any component fails, the system fails. Or they can combine in parallel; when a component fails, there is another to perform the same function.

Components in Series

If a system is composed of n components with series failure dependency, and if the failure of any one component is independent of the failure of another, the reliability of the system is the product of the component reliabilities ("product rule"):

$$P_s(t) = P_1(t) \cdot P_2(t) \cdot P_3(t) \cdot \cdot \cdot P_n(t),$$

where P_s is the system reliability and $P_1 \cdot \cdot \cdot P_n$ are the reliabilities of the n components. If the component reliabilities can be represented by the exponential law, then

$$P_s(t) = e^{-t\lambda_1} \cdot e^{-t\lambda_2} \cdot \cdot \cdot e^{-t\lambda_n} = e^{-t(\lambda_1 + \lambda_2 \cdot \cdot \cdot \lambda_n)} = e^{-t\lambda_s},$$

where the system failure rate λ_s is equal to the sum of the component failure rates. Under these conditions, the system MTBF $= \theta_s = 1/\lambda_s$.

As an example, consider a system composed of 400 components, each having a reliability of 99 percent. The system reliability is

$$P_s(t) = 0.99^{400} = 0.018 = 1.8\%.$$

Thus, on the average, this system will fail to complete 982 out of every 1000 periods of operation.

The parts (resistors, capacitors, tubes, etc.) within a component are found to obey the product rule in a similar fashion. In making a prediction of component reliability, part failure rate data, such as shown in Figure 3, must be used. A knowledge of the specific application of each part and the stresses it will experience is needed for the most accurate estimate.

When components are in series, and the product rule applies, system reliability improvement may be obtained by:

a. Increasing the component reliabilities through design improvements, derating, etc.
b. Reducing the number of functional components in the system.

Components in Parallel—Redundancy

When a design engineer has exhausted all normal means of improving the reliability of his equipment, he may consider the use of *redundancy*. That is, he may add elements in parallel with other elements in such a manner that the equipment performs its intended function when any *one* (or more) of the group of parallel elements is operating properly.

Since reliability P is a probability on the scale of zero (impossibility) to unity (100%, or certainty), unreliability Q may be defined as $1 - P$, or $P + Q = 1$. In contrast to the situation for components in series (from a reliability, not a circuit viewpoint), where the system reliability is the product of component reliabilities, it can be shown that for components in parallel (redundancy), the *over-all unreliability is the product of component unreliabilities.* Thus,

$$Q_1(t) = q_1(t) \cdot q_2(t) \cdot \cdot \cdot q_m(t),$$

where Q_1 is the unreliability of the redundant group and $q_1 \cdot \cdot \cdot q_m$ are the unreliabilities of the m redundant components. From this equation it can be shown that the reliability P_1 of the redundant group is

$$P_1 = 1 - (1 - p_1)(1 - p_2) \cdot \cdot \cdot (1 - p_m).$$

Figure 4 shows the improvement in reliability resulting from various degrees of redundancy.

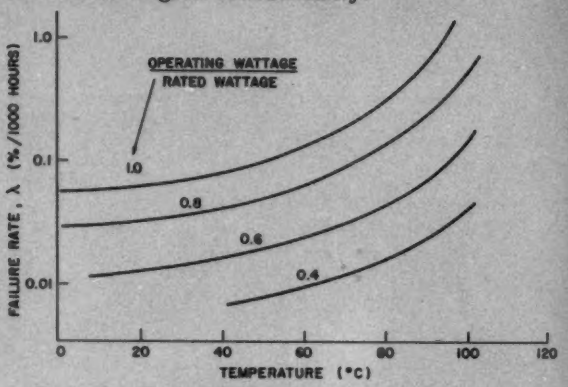


Figure 3. Typical failure rate stress curve for fixed composition resistors

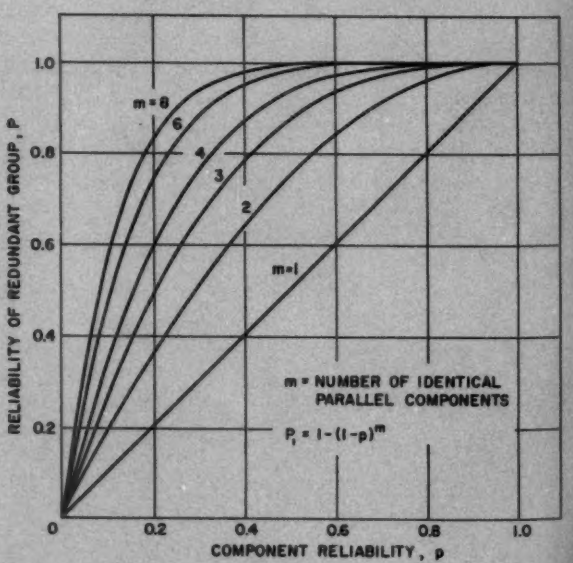


Figure 4.
Reliability of redundant groups of identical components

For a complex system, the choice between "system redundancy" and "component redundancy" is important. These two situations are illustrated by Figures 5 and 6. If, for example, a given system has m = 2, n = 5, and all p's = 0.9, calculations show that with system redundancy the over-all reliability $P_S = 0.83$ and that with component redundancy the over-all reliability $P_E = 0.95$; hence, component redundancy appears to be preferable, but consideration must be given to those factors discussed in the next paragraph before a decision is made.

So far, it has been assumed that paralleled components do not interact and that they may be activated when required by ideal sensing and switching devices. Needless to say, the latter assumption, in particular, is difficult to meet in practice, and the potential benefits of redundancy often are not realized fully. Furthermore, redundancy carries penalties of additional size, weight, cost, etc., which must be considered during trade-off decisions early in the design phase.

In many instances, equipments consist of various groupings of series and paralleled elements. Figure 7 typifies a relatively simple network of elements. The reader may wish to prove that for this network the over-all reliability is 0.94.

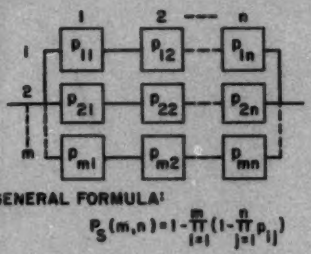


Figure 5. System redundancy

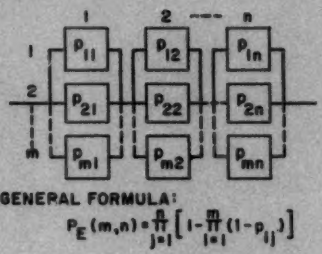


Figure 6. Component redundancy

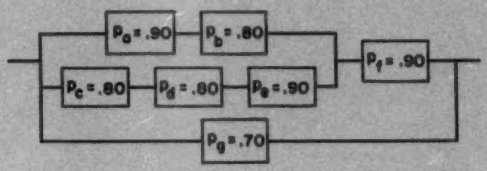


Figure 7. Reliability diagram for simple network

Tolerances and Their Effects

No two parts made to the same specifications are exactly alike. The variability in the parts leads to variability in the components and systems which they compose. This variability, as defined with respect to appropriate measurable parameters, consists of

a. A *tolerance*, or allowable variation, which is permitted principally for ease of manufacture;
b. An *uncertainty*, or error, resulting from noncontrollable causes including variability in accuracy of instruments used to measure the parameter.

The uncertainty is normally much less than the tolerance, hence further remarks will be limited to the latter.

Most electrical or mechanical parameters of a population of similar parts are found to conform to the *normal distribution curve* (Figure 8). This curve is described completely by the mean μ and by the standard deviation σ, which is a measure of the spread of the data. The numerical values of μ and σ vary, of course, from population to population; however, the area under the curve in the range of $\pm 1\sigma$ from the mean covers 68.3 percent of the particular population and the area for $\pm 3\sigma$ covers 99.7 percent. Manufacturing tolerances on parts, most frequently, are based on $\pm 3\sigma$ limits.

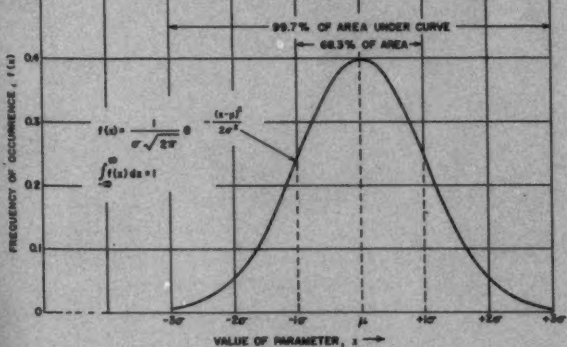


Figure 8. Normal distribution curve

General Case of Combining Tolerances

Consider the general case of a function $y = f(x_1, x_2, x_3, \cdots x_n)$, where $x_1, x_2, x_3, \cdots x_n$ are independent and each has a distribution that follows a normal curve. The distribution of the function y also will follow a normal curve having a standard deviation σ_y which may be computed from

$$\sigma_y^2 = \left(\frac{\partial y}{\partial x_1}\right)^2 \sigma_{x_1}^2 + \left(\frac{\partial y}{\partial x_2}\right)^2 \sigma_{x_2}^2 + \cdots \left(\frac{\partial y}{\partial x_n}\right)^2 \sigma_{x_n}^2,$$

provided the first approximation of the Taylor series expansion of the function is linear and the remainder terms are small, both of which conditions are often satisfied. It follows that if the tolerances on each of the x's relates to the same range of standards deviations (e.g., $T_x = \pm 3\sigma_x$), the tolerance T_y will conform to this range and may be computed directly from this equation.

Sum of Parameters

If a function y takes the form

$$y = c_1 x_1 + c_2 x_2 + \cdots c_n x_n,$$

where $c_1, c_2, \cdots c_n$ are positive or negative constants, substitution in the general equation shows that

$$\sigma_y^2 = c_1^2\sigma_{x_1}^2 + c_2^2\sigma_{x_2}^2 + \cdots c_n\sigma_{x_n}^2,$$

or, if each tolerance $T = k\sigma$, where k is the same constant for all T's,

$$T_y = \pm\sqrt{c_1^2 T_{x_1}^2 + c_2^2 T_{x_2}^2 + \cdots c_n^2 T_n^2}.$$

For example, in a circuit where the total resistance R is computed from

$$R = r_1 + 2r_2 - r_3$$

the tolerance T_R on R is

$$T_R = \pm\sqrt{T_{r_1}^2 + 4T_{r_2}^2 + T_{r_3}^2},$$

where all resistances and tolerances are expressed in absolute units, i.e., in ohms. This electrical example has an exact counterpart in the physical problem of a dimensional buildup of mechanical tolerances in an assembly.

These equations show that while the tolerance on the combination, T_y or T_R, will be numerically greater than any individual tolerance, in most instances it will be substantially less than the arithmetic sum of the separate tolerances, a condition that is of significance in many situations.

Products of Parameters

If a function y takes the form

$$y = Cx_1^{c_1}x_2^{c_2}\cdots x_n^{c_n},$$

where C, c_1, c_2, $\cdots$ c_n are positive or negative constants, substitution in the general equation shows that

$$\left(\frac{\sigma_y}{y}\right)^2 = c_1^2\left(\frac{\sigma_{x_1}}{x_1}\right)^2 + c_2^2\left(\frac{\sigma_{x_2}}{x_2}\right)^2 + \cdots c_n^2\left(\frac{\sigma_{x_n}}{x_n}\right)^2.$$

Now, if each tolerance $T = k\sigma$, where k is the same constant for all T's, and if the tolerances are expressed in *percent*, e.g., $T_{y\%} = 100\ T_y/y$, then

$$T_{y\%} = \pm\sqrt{c_1^2 T_{x_1\%}^2 + c_2^2 T_{x_2\%}^2 + \cdots c_n^2 T_{x_n\%}^2}.$$

To illustrate, in a circuit where the input impedance Z_{in} is computed as

$$Z_{in} = -\omega R L^2 C^{-2},$$

the tolerance $T_{z\%}$ on Z_{in} is

$$T_{z\%} = \pm\sqrt{T_{R\%}^2 + 9T_{L\%}^2 + 4T_{C\%}^2},$$

when all tolerances are expressed in *percent*.

Combination of Addition and Multiplication

When a circuit equation for a parameter includes both sums and products, the preceding rules may be applied successively, as required, provided care is exercised in making appropriate changes to and from percent tolerances. Often, a solution can be obtained more expeditiously, especially in situations such as frequency-sensitive circuits, if the basic equations are simplified to obtain approximate representations for particular situations.

Tolerances on Electronic Part Characteristics

In performing a tolerance analysis on an electronic circuit, care must be exercised to ensure that appropriate data are used for the tolerances on the characteristics of the parts.

(See the reliability and component engineering sections for data useful in the calculation.)

Sampling Considerations

The situation may arise in which an engineer wants to find out what kind of variation a large quantity of resistors, diodes, circuits, or complete assemblies, etc. will exhibit with respect to some characteristic of these objects, such as inverse leakage for diodes, without having any knowledge of the distribution function which applies to the characteristic.

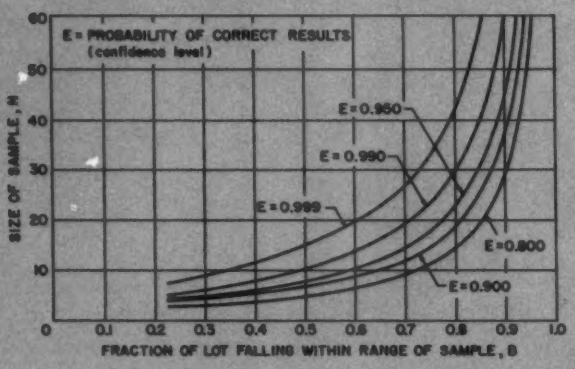


Figure 9. Sampling considerations

Consider the following problem: What is the minimum number of resistors that should be chosen in a random way from a large lot of resistors so as to be 95 percent sure of getting at least 90 percent coverage of the variations in characteristics that any resistor in the lot might exhibit? To solve the problem use Figure 9 and read across to B = 0.90 and find the horizontal line on the N scale which intercepts the curve E = 0.95. This line is defined by N = 45, which is the number of resistors required for the test.

Alternatively, the following problem may be solved: Suppose an engineer wants 90 percent coverage for any one of the characteristics of a lot of resistors, and chooses to test a random sample of 50 resistors, what degree of sureness does he have of getting the coverage he wants? The intersection of the lines B = 0.90 and N = 50 is approximately at the curve E = 0.97, which is, therefore, the answer.

continued from page 14

tion of the percent product outside the 20-unit band. The following example illustrates this fact:

1. Initial purchase specification—40 min, 80 max.
2. It is assumed that equal quantities of product are found in the classes 40-60 and 60-80.
3. The end-of-life design figure for a particular circuit is 36 or 90% of the initial lower purchase limit.
4. From the assumption of ½ the product in the 40 to 60 gain class (No. 2 above) and the curve of Figure 5, ½ the product will have a failure rate of 0.27%/1000 hours.
5. The other half of the product (gain 60-80) will not fail until gain reaches 36 or 60% of initial lower class limits. From the curve (Figure 5) the failure rate of this product will be 0.03%/1000 hours.
6. The over-all failure rate will be ½ (0.27+0.03) or 0.15%/1000 hours.

With all the foregoing information, it is now possible to better estimate the failure rate for any given circuit design. This is done for the hypothetical example given at the beginning of the paper. Catastrophic failure rate of 0.1 percent per 1000 hours may be used here as a reasonable value in lieu of actual data. Collector junction failure rate from Figure 4 is estimated at 0.1 percent per 1000 hours. Emitter junction failure rate will be zero since the emitter is not reverse biased.

Gain failure rate from the initial specification, the circuit end-point and the curve for gain failure rate, is estimated as follows:

Initial specification is 60 min. Assume 2/5 of the product is between 60 and 80; 2/5 of the product is between 80 and 100; 1/5 of the product is over 100; circuit end-of-life gain is 48 or 80% of the 60-80 class; 60% of the 80-100 class, and 48% of the 100 and up class. The gain failure rate would be $(2/5 \cdot 0.17) + (2/5 \cdot 0.03) + 0$ or 0.05%/1000 hours. The over-all failure rate would be as follows:

Catastrophic	0.1
Collector Junction	0.1
Emitter Junction	0
Gain	0.05
TOTAL	0.25%/1000 hours

The failure rate based on 340 units tested to Mil Specification Lot Acceptance procedures was 0.9 percent per 1000 hours. The result based on estimating the failure rate to the actual circuit conditions, using the methods proposed in this paper along with the hypothetical data, is 0.25 percent per 1000 hours. In the first case, one point is known. In the second, not only is a more representative figure known, but the contributing components are known and the direction for design improvement is also available.■

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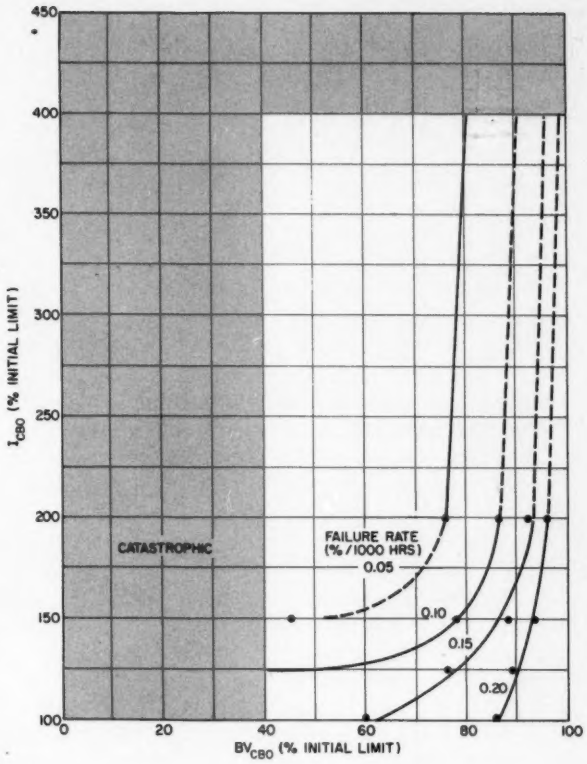


Figure 4. Constant failure rate contours (collector junction)

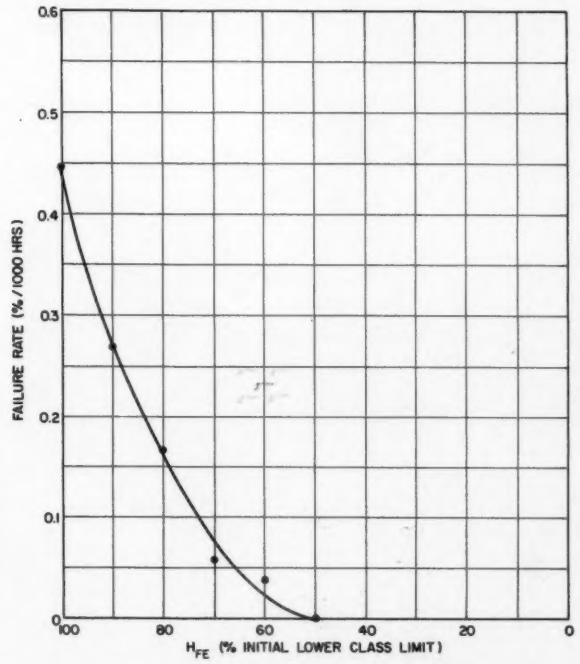
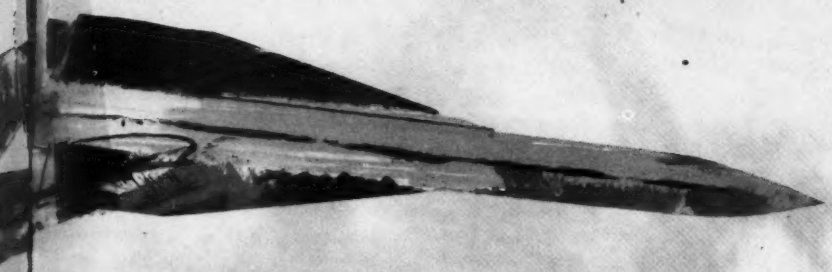


Figure 5. Gain failure rate contour

RELIABLES



E SYSTEMS

by Robert D. Reed

RAYTHEON'S extensive background in development and production of highly reliable radar equipment led to the Company's early entry into the missile field. To a large extent, Raytheon's initial success in the missile field was due to its recognition of the importance of component reliability. Airframe contractors for the Navy's Lark missile were unable to achieve a workable controlled-missile configuration of airframe, rocket motor, autopilot, and controls. In 1949 Raytheon was assigned full responsibility for a number of Larks as test vehicles for an experimental seeker the Company had developed. There followed a period of intensive redesign of all major missile control and autopilot elements in an attempt to achieve a sufficiently reliable missile to provide a suitable test vehicle. This reliability-engineered design culminated in the first recorded intercept of a target drone by a guided missile, followed by a series of successful flight tests during which several additional achievements were realized for the first time.

As an example of the lengths taken at that time in missile flight preparations, Raytheon inaugurated a 10-hour checkout period during which the guidance system was completely activated and required to perform satisfactorily on a flight simulator. When a failure occurred, the missile was repaired and the test started over until one test had been successfully completed on each missile. Before Raytheon took over the Lark program the missile had achieved only a 20 percent reliability—Raytheon raised the reliability to 80 percent.

On the basis of this success, Raytheon was awarded the Sparrow III program in 1951 and the Hawk program in 1954. The proven reliability of these missile systems was an important factor in the Navy's subsequent choice of Raytheon to participate in the Mark 2 Guidance System for the Polaris program.

In the early days of the Sparrow III program, the missile engineering group at the then Missile Systems Division was sufficiently small that a reliability-conscious management was able to instill into the design engineers a proper concern for reliability requirements. With the expansion resulting from the advent of the Hawk program and the weaponization of the Sparrow III, it became necessary to formalize the reliability activity into a reliability group. This group was chartered to promote the reliability of the Division's products in any way it could and was allowed to expand as the need arose. From the first few months of its existence, the reliability group was effective in impressing upon designers and packaging groups the fact that reliability was an important part of a product, and could be improved by good design practices, component derating, component qualification, and workmanship. It was not enough that the unit or system work on the day of acceptance by the military customer, but it should work at any time it would be needed throughout its planned life and in any environment in which it would normally be situated.

Sparrow and Hawk Reliability Programs

The initiation of the Sparrow and Hawk missile projects occurred prior to the time when the Armed Services generally recognized the need for formalized reliability programs. Raytheon, however, early saw the need for emphasis on ensuring product reliability and work proceeded on the basis that the design engineers would give appropriate attention to potential reliability areas. Later, a more organized approach was established consistent with the specific requirements of these two projects, which by that time were in the production stage.

The Sparrow and Hawk missile programs have been carried out in an environment where great emphasis has been placed on cost as well as performance. Raytheon

has been continually under pressure from its customers, the Navy and Army, respectively, to use common, standard parts and still to keep the reliability high. Techniques that have proven useful in accomplishing this task include vendor liaison, parts qualification, incoming inspection, qualified vendor lists, and failure feedback. In addition, sample environmental testing of complete missiles has been used to ensure that reliability is not degraded by the introduction of minor changes in materials, processes, and parts which are made to save cost or increase the ease of manufacture. A monthly summary of the analysis of operational problems encountered in the systems in the field, together with necessary corrective actions that have been taken to prevent future occurrence, is published for the information and guidance of the engineers and management.

Specifically, the implementation of this approach may be illustrated by the Sparrow program.

The high level of inherent design reliability of the Sparrow III missile was demonstrated during prototype approval tests, performance evaluation, and flight testing of early production models. In order that this inherent reliability be maintained continually during full scale production, it is necessary to guard against degradation brought about by subsequent design changes made for ease of manufacture, cost reduction, or component substitution. Thus, each engineering change in drawings or process specifications is scrutinized carefully for its effect on over-all missile reliability. This activity constitutes a large portion of the quality assurance engineering effort at the production plant.

When proper safeguards have been provided to ensure continuing integrity of design, the task of maintaining missile reliability falls to the manufacturing and quality control organizations within the plant and to the groups responsible for planning and supporting the efforts of these organizations. Proven engineering practices were applied in specifying functional test and inspection requirements and in developing the facilities and techniques needed for missile fabrication, processing and testing. The test and inspection facilities and procedures used at Raytheon have been designed to eliminate, as much as possible, the discretion and judgment of operating personnel as factors in the determination of product acceptability. Quality planning is aimed at integrating inspection into the various manufacturing processes at the proper place and in sufficient quantity to assure not only that engineering requirements are met but that most economical use is made of facilities, manpower, and material.

In the manufacture of any product as complex as the Sparrow III missile, errors will be made from time to time and failures occur at the various stages of manufacture or field usage. The ability to recognize the need for corrective action hinges on the accuracy and completeness of failure reporting and data analysis. Provisions are made for utilizing the output of the failure reporting system to pin-point areas wherein corrective measures will result in the greatest improvement. In particular, history has shown that the causes of failure in the field are generally identical to the causes of failure in the checkout phases of the missile manufacturing process. Thus, much valuable data which has direct correlation to field problems is obtained from the factory. Since, in general, factory data is more complete and descriptive, it has been utilized by Raytheon to a considerable degree to effect many of the individual improvements which have gone to make up the total missile reliability improvement.

The administrative details of the various activities which make up the Sparrow reliability program are of vital importance. Raytheon maintains a handbook of standard operating instructions which describes in detail the procedures required to execute various departmental responsibilities. Through daily implementation of these procedures, Raytheon continually ensures the defense readiness of the Sparrow III missile.

Specific Reliability Assurance Activities

Among the specific activities that have proven valuable in the missile reliability programs, the following are significant:

ENVIRONMENT DETERMINATION: Raytheon has conducted in the course of the Hawk program a project to determine the external and the self-generated environment for the Hawk system. A great deal of research has gone into determination of missile environment through instrumented flights, analysis of transportation environment, and research of available literature. Instrumented trailers and truck-borne major items have been run over the rough courses at Aberdeen Proving Grounds. Missiles and missile systems have been left exposed during worst desert and arctic environments.

Results obtained from this study have been compiled to give the missile-system environment and have been extrapolated into component-part environments for use in product design and in purchasing and evaluating parts. Self-generated environments measured in the course of qualification and approval tests have served to confirm original design figures as well as to enable Raytheon to check out trouble spots and concentrate effort on redesign of component parts which would be subject to future reliability failures.

PART DISSECTION: Component part specialists at the several engineering and production plants have extensive experience in the analysis of failed parts returned from test activities and the field. Further, they analyze proposed new products for incorporation in missile systems for location of inherent design weaknesses and for possible sources of trouble in production. These men also have had considerable experience in the evaluation of improvements and in liaison with manufacturers, to persuade them to improve products beyond normal military requirements.

VENDOR QUALIFICATION AND SURVEILLANCE: The Reliability Department maintains a "Qualified Vendor List"

for all parts which have been tested and which show potential usage in the various systems designed for the Armed Services. This list is a positive approach whereby a number of vendors is established as being approved sources for part procurement. This approval is given only after a knowledge of the vendor's performance is gained through preliminary tests of representative samples, use of products, and visits to the vendor's plant. Great care is used to avoid the situation where decisions are made on the basis of a small number of selected or pre-production samples.

The vendor qualification and surveillance program is a continuing effort and Raytheon specialists frequently visit a vendor's plant to make suggestions for part improvement to ensure that the reliability requirements are met. Personnel involved in these visits also make an evaluation of the vendor's facilities for purposes of future procurement. This evaluation includes a personal inspection of the manufacturing area. Particular attention is given to evidence of the management's interest in reliability and quality control, the documentation of process and inspection procedures, and the sampling plans and acceptance criteria employed. This type of evaluation has helped considerably in reducing the large number of replacements, retrofits, and rejections often encountered in a manufacturing program.

FAILURE REPORTING AND CORRECTIVE ACTION: Formal failure reporting programs are in operation for each system. Field and in-plant failure data are tabulated by electronic data processing equipment and analyzed to establish significant sources of failure. As these sources are identified, action is initiated to establish the cause and appropriate correction. Reliability personnel monitor the entire failure correction and reporting cycle to ensure that the desired results are obtained.

QUALITY MONITORING AND EVALUATION: The Quality Monitoring Program ensures that component and assembly quality are being maintained to promote end-product reliability. This activity provides for:

(a) Independent evaluation of a small, random sample of parts and subassemblies drawn from stores or production line;

(b) Independent evaluation of each missile prior to customer acceptance which emphasizes the strict comformance to procedures during final test, the performance of additional testing where marginal operation is apparent, and the absence of intermittent failures during the entire test program;

(c) Independent visual check-inspection of a sample (at least 50%) of the completed missiles after final test;

(d) Independent environmental test of a sample of completed missiles;

(e) Independent monitoring of comformance to inspection, test, and process procedures by all concerned.

Polaris Reliability Program

Raytheon currently is providing industrial support to the Massachusetts Institute of Technology, Instrumentation Laboratory, in the development and production of Polaris Mark 2 Guidance System. Basic design concepts for the Mark 2 System originate at MIT/IL; however, actual circuit design and development are done both at MIT and Raytheon. At Raytheon, elements of the Missile & Space Division, the Aero/Weapons Division, and the Industrial Components Division are involved in this program.

Raytheon's reliability effort on the Mark 2 System begins at the circuit-breadboard stage and continues through circuit development, product engineering, manufacturing, test and inspection. Later, reliability efforts will be extended to cover performance of the guidance package when installed in the missile for laboratory and field tests. As a part of the reliability program, particular attention is given to:

(a) Environmental Determination
(b) Reliability Estimation and Apportionment
(c) Reliability Indoctrination
(d) Vendor Control
(e) Component Parts and Materials Engineering
(f) Reliability Design Reviews
(g) Specifications and Process Reviews
(h) Production Test Plan Reviews
(i) Production Environmental Tests
(j) Malfunction and Failure Reporting
(k) Reliability Analysis of Flight and Test Failures
(l) Reliability Test Planning
(m) Program Data Evaluation
(n) Inter-Service Data Exchange
(o) Reliability Liaison.

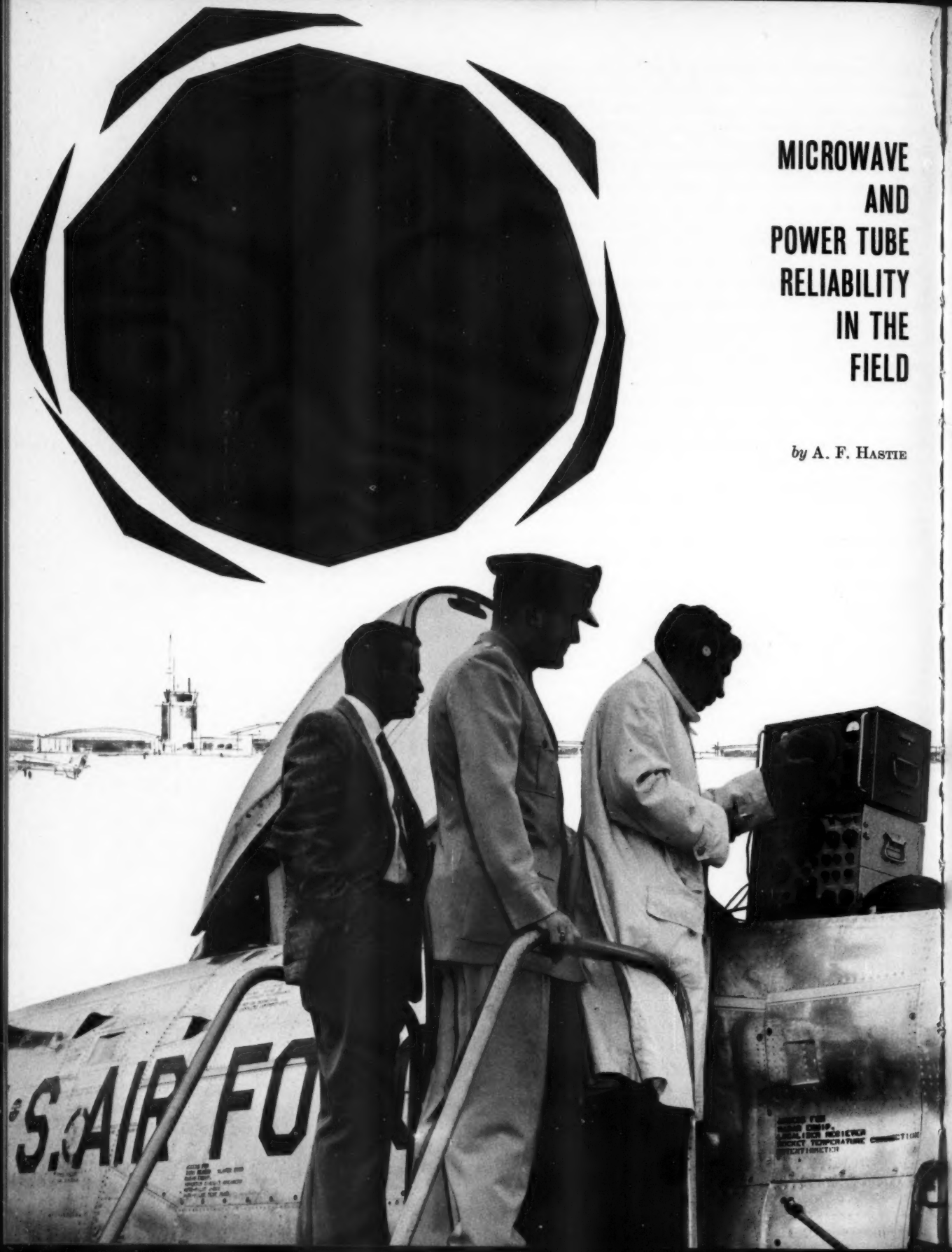
The reliability control function for the Polaris project is vested in a single organizational group at Raytheon, namely, the Reliability and Inspection Department of the Bedford Laboratory. To carry out this responsibility, a Polaris Reliability Coordination Group has been established with a staff of capable reliability specialists, engineers, and mathematicians. In addition, management has defined certain functions and formal controls within the Reliability and Inspection Department to provide it with authority for over-all reliability surveillance.

In order to adequately perform the industrial support function, experienced Raytheon circuit design, product design, and quality assurance engineers are in residence at the MIT/IL. As questions and problems of reliability, quality assurance, maintainability, and producibility arise at MIT/IL during circuit design and development, these engineers follow long-established practice and call upon specialists within Raytheon for assistance when needed.

The effectiveness of this reliability program is evident from the results obtained during early stages of the program. Of particular significance are the improvements in the welded-module assemblies which are described elsewhere in this issue of ELECTRONIC PROGRESS.■

MICROWAVE AND POWER TUBE RELIABILITY IN THE FIELD

by A. F. Hastie



MICROWAVE and power tube devices encompass a family of relatively high-cost electron tubes usually identified as magnetrons, klystrons, amplitrons, backward-wave oscillators, etc. Such devices are employed as high-power radio-frequency generators and amplifiers in most military ground-based shipborne and airborne radars. They also perform key functions in various other applications such as troposcatter communications, commercial heating and telemetering systems.

To properly maintain electronic systems employing microwave devices, it is apparent that the maintenance technician must be trained to diagnose problem symptoms and to take remedial action. It is also evident that over-all system maintainability does, to a large extent, depend upon design parameters which permit the technician opportunity to perform his assigned tasks. Among other things, the reliability of a system is closely related to both designed maintainability and the training of a technician. This paper will attempt to illustrate how substance can be added to the terms "maintainability" and "reliability" insofar as microwave tube devices are concerned.

Statistical quality control and test procedures have been established by component manufacturers to monitor design characteristics during production and to assure product reliability prior to delivery. In spite of these in-plant quality control and quality assurance programs, this same product can be found to exhibit poor performance and reliability in the field. Evidently achievement of a long life microwave and power tube design capability is not, by itself, sufficient to assure achievement of long life in a field environment.

Several microwave and power tube studies, conducted in the field by a variety of competent engineering agencies, have already determined many of the contributing factors known to affect microwave tube reliability. As a result of the recommendations of these agencies, a number of design improvements were incorporated. Although these improvements influenced the manufacturer's yield of good tubes which met specified in-plant production and life test requirements, the degree of early life tube removals in the field remained relatively unaltered. Tube field reliability studies conducted by Raytheon indicate major problem areas to be: a) Lack of practical tube information in the hands of a maintenance technician to permit him to more accurately diagnose a problem, and b) Inadequate feedback of field performance data to help the tube manufacturer make product improvements in line with field requirements.

Modern radars employing magnetrons, klystrons, amplitrons, and other such devices are becoming more and more complex, which means tube field problems will become correspondingly more difficult to define and remedy. The problem of soaring military microwave and power tube replacement costs, therefore, will become even more staggering. Raytheon's experience indicates that improved field performance of microwave and power tube devices can best be achieved when in-plant design engineering and quality control capabilities are augmented by a well-organized, systematic field program.

Once the full capabilities of a product have nearly been attained in a field environment, design engineering and quality control techniques applied to a product can almost always be improved. As a result of its field reliability studies, Raytheon believes that until the contributing factors to a tube field problem are properly defined, many design and quality control improvements will have little impact upon the operational capability of a radar system.

Organized field programs can be patterned after that which was jointly and successfully worked out with Headquarters Air Defense Command (USAF) regarding the RK6410A/QK338A type magnetron. In this case, forceful military management action coupled with the consulting services supplied by Raytheon's Microwave and Power Tube Division resulted in a dramatic improvement. The RK6410A/QK338A magnetron life was increased from an average of 300 hours during 1958 to about 2400 hours by the end of 1960. Considering only direct tube replacement costs, Headquarters Air Defense Command achieved a savings of about 83 percent between the cost per tube radiate hour of operation realized in 1958 to that attained in 1960. It is important to note that this life improvement and reduction in replacement cost was accomplished without any modifications to the RK6410A/QK338A magnetron.

A program of this nature helps to establish a degree of tube field performance more nearly compatible with the design capabilities of an existing product. It provides the tools necessary for maintenance personnel to more efficiently define and remedy problems associated with microwave tubes. It provides, also, the vehicle to feed back accurate and timely data which can more efficiently direct design engineering toward product improvements. The techniques and procedures developed can then serve to circumvent field problems on the more complex and costly tube devices of future radars. It is Raytheon's contention, therefore, that field programs of this type are necessary if the full design capabilities of a microwave and power tube device are to be realized. The principal program benefits can be listed as an improved weapon capability at a reduced maintenance cost for the military, and an improved product reputation for the manufacturer.

A Successful Tube Field Program

The following example of a successful tube field program will be outlined in three phases. Phase I demonstrates the approach normally taken by a tube manufacturer when deficiency reports reveal an alarming state of poor product reliability. Phase II demonstrates a more thorough investigation conducted under a Government-sponsored contract, and Phase III illustrates a

last and desperate effort to determine why the efforts expended during Phases I and II failed. The case at hand follows the RK6410/QK338 type magnetron and AN/FPS-6 radar height finder through each phase.

1. PHASE I—Historical Background

During 1953 the tube and systems manufacturers, along with the cognizant Military Programs Manager, agreed that the RK6410/QK338 had reached a point in the state of the art whereby time and money dictated that development efforts cease. Engineering evaluations determined that the tube and system were compatible, and that they would meet the requirements of a Military Purchase Specification. In the spring of 1954, Raytheon completed the production run of RK6410/QK338 magnetrons, and the bulk of deliveries had been made to an Air Force depot as replacement spares.

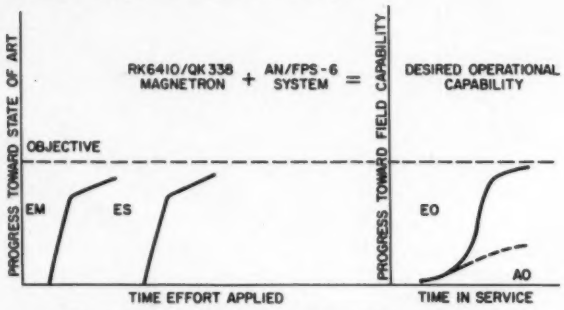


Figure 1. Desired operational capability of RK6410/QK338 magnetron and AN/FPS-6 system

Figure 1 academically describes a progression of efforts applied by both industry and the military to achieve the ultimate objective of a desired operational field capability. The curves "EM" (magnetron effort) and "ES" (system effort) illustrate development progress toward an objective until, at the point "P", development ceases and production starts. A compatible tube and system, therefore, should equal some desired operational field capability after sufficient military training and time in service has been applied. The curve "EO" (operational effort) demonstrates military progress toward an operational capability; progress being initially slow until the training effort is complete. Upon completion of training, the curve "EO" should rise rapidly to the desired capability of a weapon. In the case of the RK6410/QK338 magnetron and the AN/FPS-6 radar, however, the desired field capability was not initially achieved.

During the latter part of 1954 and early 1955, reports of magnetron mortality became alarming. Two major complaints were made known to the tube manufacturer: 1) Approximately 50 percent of the magnetrons failed to oscillate when first installed, and 2) Those magnetrons which did not fail initially generally failed before attaining 40 hours of life.

Raytheon could not readily explain this poor magnetron field performance and embarked upon special in-plant investigations. Since there was no practical way to accelerate shelf life, a group of 70 magnetrons which accumulated the longest shelf time were drawn from Air Force stock and submitted to tests. Of the 70 tubes involved, some of which were early development tubes better than four years old, only 3.7 percent failed tests. This was considered, at the time, to be an outstanding example of the quality and reliability of the tubes being shipped, especially since each of the test failures was attributed to a loss of vacuum during storage. The tests, however, did not explain the 50 percent attrition rate reported by the User Activities.

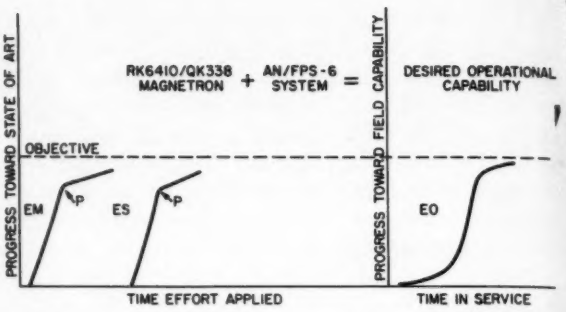


Figure 2. Failure to reach desired operational capability

A review of in-plant tube performance, as well as special tests cooperatively worked out with the systems manufacturer, failed to reveal the factors contributing to the 40 hour magnetron life in the field. At this stage, the in-plant facilities available to a tube engineer had been exhausted without producing an adequate explanation for the RK6410/QK338 magnetron field problem.

Since the causes of the tube problem could not be defined by in-plant engineering techniques and facilities, one further step was taken. Again with the cooperation of the systems manufacturer, a team consisting of one tube engineer and one systems engineer visited three field radar installations. By combining their individual talents with a bit of detective work, the major field problem was defined as a lack of technical tube information available to military field personnel. In an effort to reduce the problem, several hundred copies of a brochure entitled, "Handling, Installation and Operation of the RK6410/QK338 Magnetron as Used in the AN/FPS-6 Radar," was jointly compiled, published and distributed to the field by both manufacturers in June 1955. Believing that the instructions contained in the brochure would resolve the magnetron field problem, Phase I of the RK6410/QK338 magnetron field problem was brought to a close.

2. PHASE II—Tube Reliability Study for Rome Air Development Center

Fortunately, the Rome Air Development Center, Griffiss AFB, recognized the need for further investigations of the reliability of high-cost tube devices for new

type radars. A contract was awarded Raytheon in June 1955 to conduct such a study upon several different magnetron applications, one of which pertained to the RK6410/QK338 magnetron. The results of these studies are contained in Volumes I and II of the Final Engineering Report entitled, "Magnetron Performance and Reliability in Equipments," conducted under USAF Contract AF30(635)2864 dated 13 June 1955 to 31 October 1956.

After a short period, this organized approach to a tube field problem revealed that magnetron performance was indeed very poor. Analysis of the data accumulated is illustrated by the curve "AC" (actual operation) shown

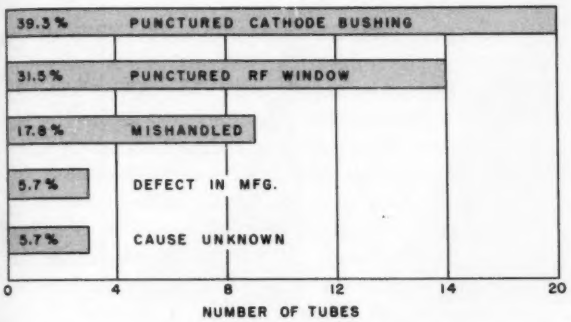


Figure 3. Breakdown of analysis on 51 sample RK6410/QK338 magnetrons that failed in field environment

in Figure 2. Although the magnetron brochure distributed in June 1955 by both tube and equipment manufacturers was found to help reduce RK6410/QK338 field consumption, the brochure fell far short of the anticipated impact. It was later determined that since the brochure was not an official Air Force document, many military personnel were reluctant to accept some of the recommendations it contained.

Throughout the course of this reliability study for RADC, the tube manufacturer acquired a more intimate appreciation of the military maintenance complex. Approximately 90 percent of the failures were attributed to misunderstandings and lack of sufficient technical tube information available to the maintenance technician. Figure 3 gives the results of analysis on 51 sample RK6410/QK338 magnetrons which failed under 24 hours of operation in the field and were returned to the factory for analysis. Only three of the defective tubes were attributed to manufacturing. Although a degree of improved performance is revealed by Figure 4, the field life capability of an RK6410/QK338 was still far short of its potential design capabilities.

This reliability study for RADC recommended:

1. An Official Technical Manual pertaining to general magnetron handling, installation, and operating procedures for the maintenance technician. (USAF T.O. 12-1-48 entitled "Magnetron Handling, Installation, and Operation" was published in July 1958.)
2. Closer coordination and stronger lines of communications between the tube manufacturer and the Military User Activities. (Raytheon carried this out at no cost to the Government by establishing a special engineering group now known as Product Service Department.)
3. A training film depicting various examples of proper handling and operation for high-cost microwave tubes. (USAF Training Film TF1-5331 entitled "Maintenance of Microwave Power Tubes" was completed in 1959 and is available from Air Force Film Library, St. Louis, Mo.)
4. A set of film slides to supplement the movie film which could be produced for specific tube and system applications. Film slides were recommended because of the ease with which they could be edited and brought up to date at minimum cost. (USAF Film Strip FS 1-2974 entitled "Magnetron Care, Handling, and Storage" was produced in 1957 for the RK6410/QK338.)
5. Technical Information Bulletins by each of the many tube manufacturers. (Raytheon has endeavored to fulfill this requirement by producing

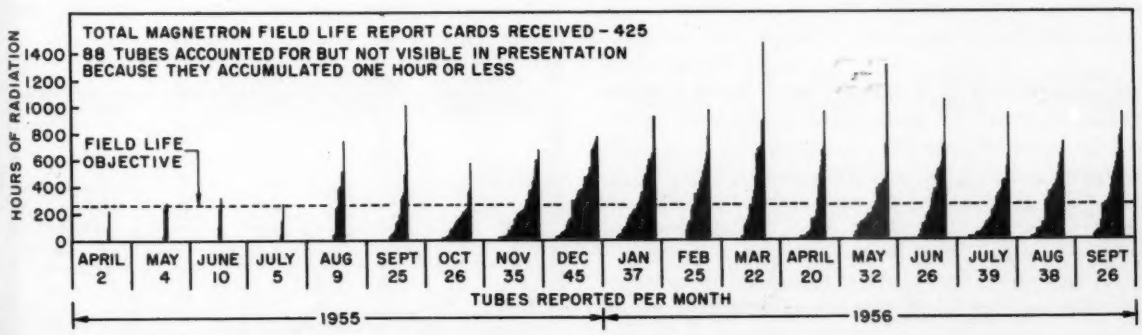


Figure 4. RK6410/QK338 field life report (April 1955 - September 1956)

and distributing many such bulletins as maintenance aids.)

6. Some means be established for acquiring reliable and timely feedback of tube data on a widespread field problem. (The Product Service Department of Raytheon has cooperatively worked with the various Commands for a mutual exchange of information.)
7. RK6410/QK338 magnetron improvements. (Raytheon modified the tube to provide a more efficient cathode, and to incorporate the oil vent pipe. This tube is now identified as the RK6410A/QK338A.)
8. AN/FPS-6 radar improvements. (The systems manufacturer cooperatively provided several modifications which helped to make the magnetron and radar more compatible in a field environment.)
9. A more realistic tube test specification for Military Tube Purchase Requirements. (Raytheon revised the RK6410A/QK338A specification sheet to more nearly meet the environmental conditions then existing in the field.)

The study contract for RADC was brought to a close in October 1956. As a result of the recommendations listed above, the RK6410/QK338 magnetron field problem was thought to be resolved. The chart shown in Figure 5 sums up the efforts of Phase II and reveals the anticipated operational capability. The dashed lines over curves "EM" and "ES" indicate a new magnetron effort and a new system effort toward product improvements recommended as a result of the study. The curve "ET" represents a new effort on the part of the military to provide special magnetron training. The combination of efforts by both military and industry should result in an operational capability exceeding that originally desired.

3. PHASE III—A New Aggressive Approach to the Tube Field Problem

During the early part of 1958 after engineering improvements to both the magnetron and radar system had been accomplished, field performance reports were again unsatisfactory. Raytheon, at no cost to the Government, focused attention upon the new RK6410A/QK338A magnetron to determine the reason for a field problem. Again, data was collected and analyzed to establish failure causes and trends. The initial results were quite discouraging, as illustrated in the chart of Figure 6. It was found that in spite of the manufacturers product improvement efforts and military magnetron training efforts, the curve "AO" (actual operation) was little or no better than that level of performance measured in 1955-56 during Phase II. Obviously, the cause for a missing reliability factor (between the desired capability and the actual capability) had yet to be determined and remedied.

This missing reliability factor caused the Office of the Director of Electronics for Headquarters Air Defense Command to take direct action. The responsibility for a field tube improvement program was delegated by the Headquarters Command to the then Director of Electronics, Western Air Defense Force at Hamilton Air Force Base. With a single tube engineer offered by Raytheon as a consultant to WADF, a pilot tube field program was initiated. This group at Hamilton Air Force Base took certain basic tools recommended by the manufacturers and organized a plan of attack.

An initial "look-see" program was established at three radar squadrons to work out the necessary details. The objective was to determine if indeed an approach from the field, supported by the experience already gained by tube engineering, could now accomplish that which "paper studies" had failed to do. The results obtained at these three sample squadrons proved gratifying and indicated that the RK6410A/QK338A magnetron had a field life capability of at least 800 hours. The next step was to produce a military directive to enforce the procedures and techniques developed at the three sample squadrons and apply them to many more squadrons. A document identified as WADF Letter 66-10, "Magnetron/Klystron Operations Improvement Program," dated 15 October 1958, was compiled and implemented at Hamilton Air Force Base. This letter established the military policies on requirements, responsibilities, and procedures for each Air Division and

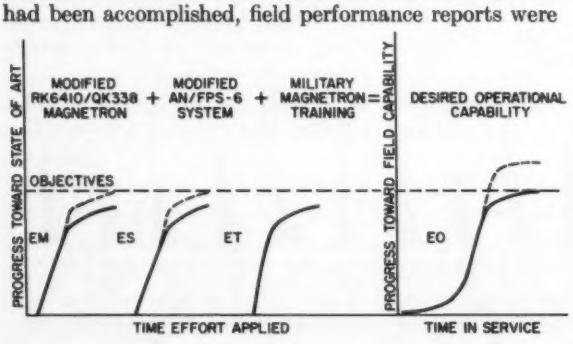


Figure 5. Desired operational capability of modified RK6410/QK338 magnetron and AN/FPS-6 system

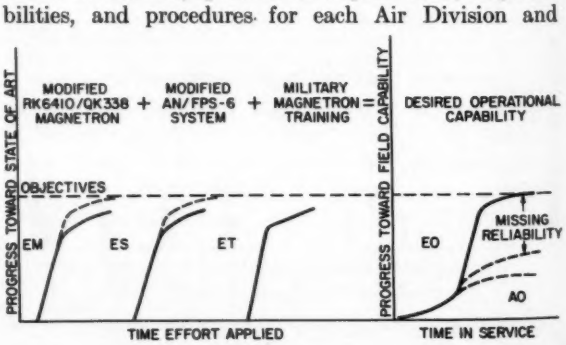


Figure 6. Failure to reach desired operational capability with modified RK6410/QK338 magnetron and AN/FPS-6 system

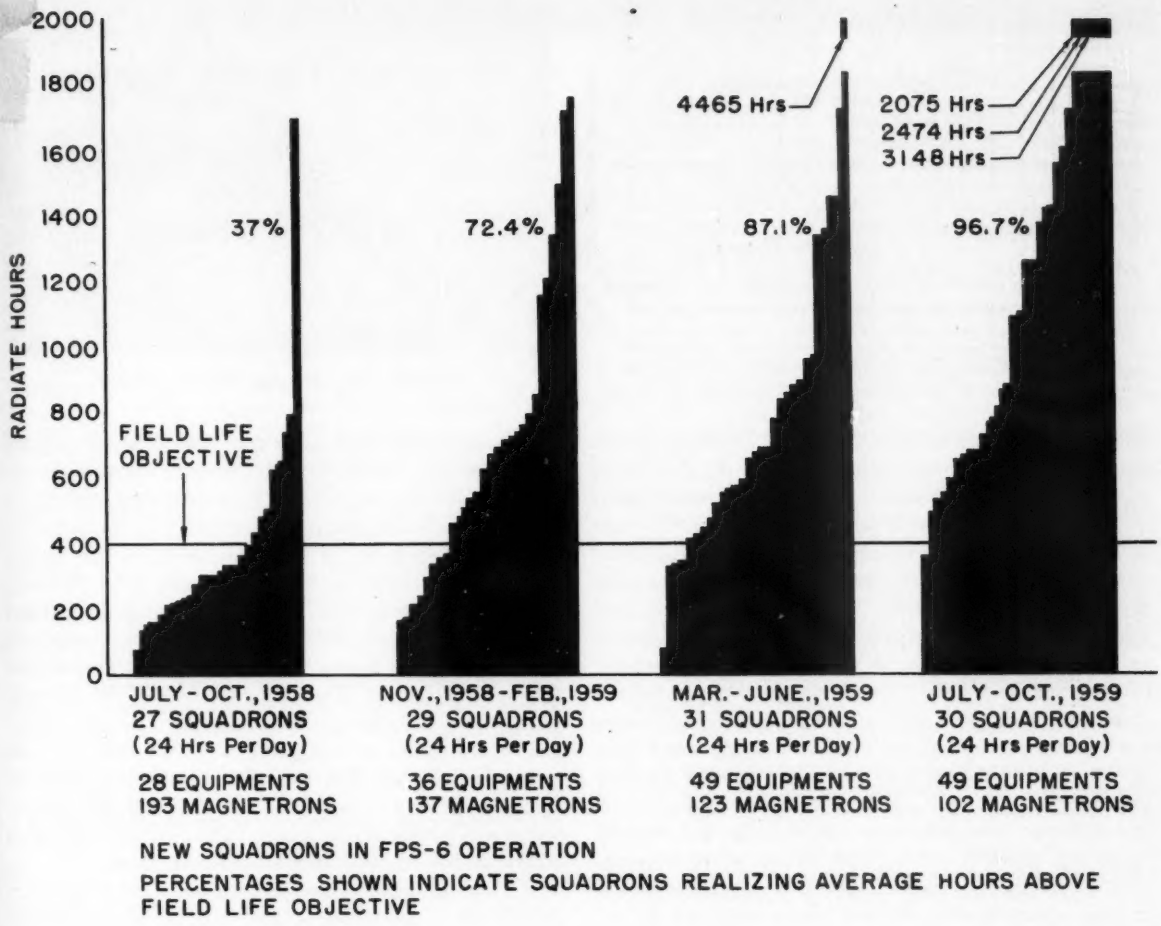


Figure 7. Magnetron life average by squadron

Squadron Commander. Figure 7 graphically illustrates the dramatic impact of WADF Letter 66-10 on the approximately 30 radar squadrons involved. The set of histograms demonstrates how the number of short life magnetrons gradually diminished as squadron confidence and efficiency improved. Note that only 37 percent of the squadrons achieved a 400-hour average tube life during July-October 1958, and these squadrons exceeded the initial 400-hour goal by 96.7 percent during July-October 1959.

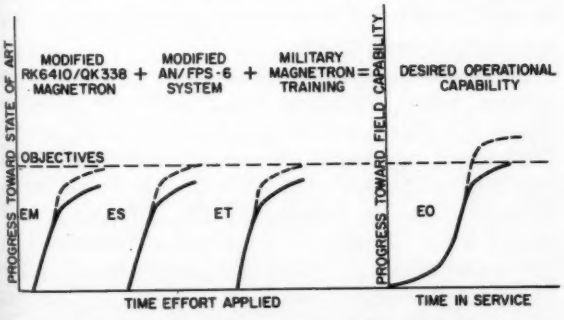


Figure 8. Final program effort to attain desired operational capability

In Figure 8, the dashed line over the curve "ET" (training effort) represents a training effort enforced by Air Defense Command Management Action. This final effort was then believed to be that required to produce an operational capability exceeding the original desired level of curve "EO."

After the "look-see" portion of the program had proven successful, Headquarters ADC incorporated the entire program into the Air Defense Command Manual ADCM 66-6 and implemented the action necessary to enforce military management and control for the entire Command.

Analysis of a few thousand special magnetron failure report cards forwarded to Raytheon during the period from mid-1958 to the end of 1960 showed the RK6410A/QK338A magnetron average tube life improvement to be about eight to one. Figure 9 illustrates a magnetron average life increase from about 300 hours to 2,400 hours

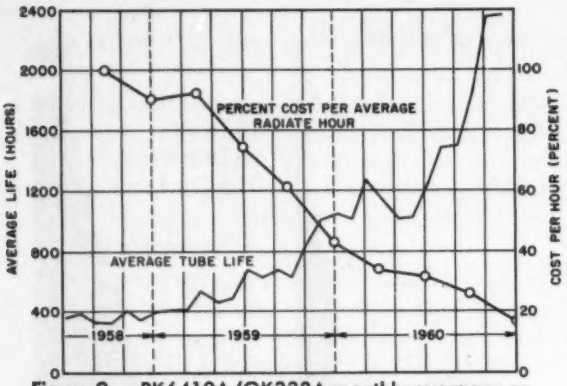


Figure 9. RK6410A/QK338A monthly averages as reported by various Air Force sites

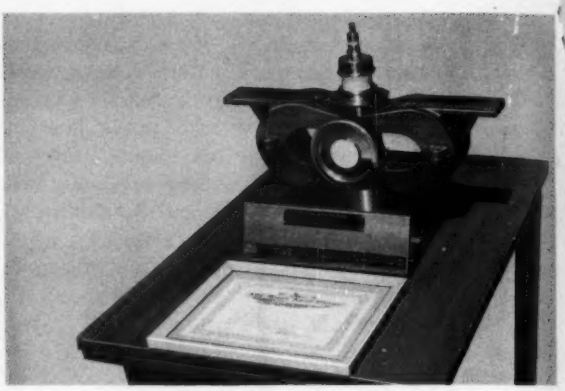


Figure 10. Maggie Trophy Award

for the entire Air Defense Command. This far exceeds the 800-hour capability estimated early in 1958 as a result of the tests conducted at the three sample sites. It must be noted also that this magnetron life was achieved without any modification to the RK6410A/QK338A magnetron. The curve labelled "Percent Cost per Average Radiate Hour," was based upon a typical RK6410A/QK338A purchase price, and demonstrates an 83 percent reduction in replacement tube cost between 1958 and 1960. Raytheon naturally suffers a short-term loss when such a tube replacement business is virtually eliminated, but this is less significant than the long-term business gain realized by a better product reputation in the field. Perhaps a more efficient use of the military tube procurement fund for replacement tubes can possibly be devoted to new tube developments. Raytheon believes that the accomplishments of Headquarters Air Defense Command can be attributed to four major points:

1. Command acceptance of a tube consulting engineer who was directly supported by the manufacturer's laboratory facilities.
2. The organization and forceful implementation of a military Magnetron/Klystron Operations Improvement Program by Headquarters ADC.
3. Command encouragement and recognition of the maintenance technician's efforts using the incentive of a "Maggie Trophy Award." The trophy was awarded only to those squadrons achieving longest magnetron life within certain periods. The longest life so far recorded for the RK6410A/QK338A stands at better than 10,000 hours.
4. Command adoption of a philosophy to employ the magnetron as a "barometer" of maintenance efficiency.

The dividends realized by Headquarters Air Defense Command can be cited as a greatly improved weapon capability at an annual savings estimated to be in the millions of dollars. Raytheon benefited by a greatly improved product reputation and a more realistic accounting of tube field capability. The RK6410/QK338 tube problem which initially seemed insurmountable in 1955 was finally brought to a successful conclusion after three almost separate approaches to the problem.

Looking back in an attempt to define the major contributing factor to this microwave tube problem, we find no single item to indict. It is Raytheon's opinion that the habit of "tube changing" as an expedient method of maintenance might have been the greatest influencing factor. Expending a few $1.50 electron tubes from a radio receiver in lieu of several costly man-hours spent in analyzing a circuit can, in most cases, be justified. The tube-changing habit, however, appears to have invaded the area of high-cost microwave and power tubes, where indiscriminate changing might involve multi-thousand-dollar devices.

A technician not provided with adequate tube information as a maintenance tool can hardly be blamed for looking upon these devices with suspicion. If he cannot properly define a tube problem, the technician will invariably regard the tube as a source of trouble. The need for programs which will provide direction and support of tube devices to both military and field augmentation personnel is evident. When such a need is fulfilled, field personnel will prove their capability to adapt the basic program principles to other similar tube devices regardless of who manufactured the product. Military maintenance and augmentation personnel of the Air Defense Command have already proven this capability for adaptation.

Although the example cited above pertains to a ground radar application, shipboard and airborne radars can achieve similar tube field life improvements. Each basic application, however, presents different maintenance, logistics, and operational problems which must be carefully considered. The Microwave and Power Tube Division of Raytheon will continue to provide a product service for end-use systems and plans to expand this service to the more complex applications of amplitrons, backward-wave oscillators, travelling-wave tubes, etc.■

INVENTIONS

BONUS PAYMENTS for patent disclosures were received by:

JOHN J. KELLEHER.....Voltage Doubling Full Wave Phase
IRVING GOLDSTEIN.....Ferroelectric Traveling Wave Parametric Amplifier
ROBERT L. WYCKOFF.....Digitally Controlled Variable Frequency Oscillator
STEPHEN A. SLENKER.....Self Balancing Circuit
NATHAN FREEDMAN.....Time-Synthesized Pulse Compression Technique
FRANCIS A. GICCA.....Phase Coherence
R. M. JOHNSON.....Vacuum Tube Window Assembly
G. MACMASTER.....Vacuum Tube Window Assembly
HERMANN STATZ.....Semiconductor Negative Resistance Device for Microwave Frequencies
ROBERT A. PUCEL.....Semiconductor Negative Resistance Device for Microwave Frequencies
GEORG RUPPRECHT.....Ferroelectric Signal—Translating Device
DUANE B. HAAGENSEN...Oil Well Microwave Tube
T. W. R. EAST.....Storage Tube MTI

PATENTS

ABSTRACTS OF RAYTHEON PATENTS issued during March and April, 1961. The following are abstracts of the technical content of the patents and do not necessarily reflect the scope of coverage being claimed in the patents. Copies of the patents may be obtained through Raytheon's divisional libraries.

RICHARD C. MARHOLZ, "Cathode Ray Tube Indicator System," Patent No. 2,974,192

This patent relates to a structure for mounting a television kinescope tube including a ring-like clamp around the dome of the tube adjacent to the face of the tube, a chassis surrounding the neck of the tube, the plane of the chassis being perpendicular to the tube axis, adjustable connectors between the chassis and clamp whereby the chassis can be forced against the dome of the tube adjacent to the tube neck, and means for securing the chassis and the clamp to an enclosure so that the tube is supported in the enclosure entirely by its dome portion.

ROBERT F. ARNESEN, "Balanced Discriminator," Patent No. 2,974,287

This patent relates to a balanced discriminator circuit which utilizes a differential capacitor in the transformer secondary of the discriminator input circuit. Adjustment of the circuit can be easily made so that the slope of the discriminator curve may be set to very close tolerances. A large number of units can be produced and still maintain consistent results from unit to unit by an easy screwdriver adjustment, thus saving a large amount of test time in production.

ROBERT A. FRYKLUND, "Pulsed Oscillator Having Oscillation Terminating Means Independent of Initiating Pulse," Patent No. 2,974,293

This patent relates to a circuit for termination of oscillations independent of the dwell time of keying contacts by means of a fixed energy pulse from a thyratron discharge circuit which triggers the oscillator by momentarily overcoming the preset bias level of its grid control circuit. Erosion of the keying contacts is prevented by this circuit.

HANS KLEMPERER, "Moving Target Radar System," Patent No. 2,974,317

This patent relates to an MTI radar system which includes separate antennas one of which lags slightly behind the other by a small fixed angle. Received signals are fed to a plurality of storage tube. The two directional antennas rotate at the same speed and radiate separate beams of pulses so that the first beam is recording information while the second beam is comparing information previously recorded. In this way moving targets are able to be distinguished.

HUSTON W. COCKRILL, "Indirectly Heated Cathodes," Patent No. 2,975,322

This patent relates to an indirectly heated cathode for magnetrons in which the cathode structure includes a sintered pellet having an imperforate surface facing the heater to prevent migration of electrons to the heater.

LEONARD B. EMERSON, RICHARD P. CURTIS, "Indicating Device," Patent No. 189,914 (Design)

This patent relates to the DE-708 "Angler" indicator design.

AMOS J. CARR, JR., "Dual Phase-Modulator Circuit," Patent No. 2,976,491

This patent relates to a phase modulation system which is used in the control of machine tools. The input signal represents combined X and Y vectors and the output signal is phase modulated as a function of the deviation of the magnitude of the input signal. The sense of the phase modulation depends on whether the magnitude of the input signal is greater or less than that of a selected reference.

ROYDEN C. SANDERS, JR., WILLIAM R. MERCER, "Frequency-Scanning Radio Receiver," Patent No. 2,977,465

This patent relates to a frequency scanning radio receiver which cyclically varies the resonant frequency of a tuned channel relative to the frequency of signals from a source by an amount less than the width of the tuned channel in order to distinguish a coherent signal from noise. When the reactance-swept local oscillator locks upon a signal, a phase comparator is activated to measure the coherence of a true signal as opposed to an instantaneous burst of noise energy. The presence of a coherent signal in the narrow increment of the receiver scanning spectrum generates a dc bias to control a locking and recycle circuit which maintains the sweep circuit locked on a signal as long as it remains coherent. In the absence of a coherent signal, sweeping is again initiated.

WILLIAM C. BROWN, EDWARD C. DENCH, "Electronic Discharge Devices of the Magnetron Type," Patent No. 2,977,502

This patent relates to a transverse magnetic field electron tube having a reentrant electron beam and a non-reentrant anode vane delay line such as the Amplitron.

ORWALD E. KIENOW, "Dielectric Nose Cone Antenna," Patent No. 2,977,593

This patent relates to a dielectric nose cone antenna for a missile. The dielectric radiating element forms the tip, or front portion of the nose cone; and is streamlined to provide a continuous surface with the rear portion of the nose cone. A waveguide is connected to the dielectric radiating member by means of a waveguide matching nubbin.

ARTHUR B. SLATER, "Signal Seeking Tuners," Patent No. 2,977,466

This patent relates to a signal-seeking tuner in which a relay circuit and control tube are provided to disable an AFC loop following a loss of the signal in the IF amplifier. The local oscillator tuning motor voltage is fed to a delay circuit in order to disable a control tube for the locking circuit long enough to permit the local oscillator scanning motor to sweep the local oscillator beyond the frequency of an undesirable lock signal.

KENNETH L. SULLIVAN, RAYMOND C. MCNAMARA, "Insulated Wire Stripper," Patent No. 2,978,565

This patent relates to a thermal wire stripper for stripping insulation from a wire without the use of a cutting edge. A pair of movable hand-grip jaws have high resistance wires attached at one end so that a wire conductor can be placed between the high resistance wires. When current is supplied to the high resistance wires, the insulation on the wire conductor is heated by the flow of current in the high resistance wires, and a preselected portion of the insulation on the wire conductor is removed as the conductor is withdrawn from between the high resistance wires. Such operation prevents damage to the wire conductor as might result from mechanical wire strippers.

JAMES C. DAVIS, JR., "Stable Oscillators," Patent No. 2,978,650

This patent relates to a stable oscillator in which a resonant tank circuit is coupled to a flip-flop multivibrator so that the latter is triggered by the tank circuit output signal. The unique coupling of the frequency-controlling tank circuit to the oscillator allows the maintenance of an extremely stable frequency and amplitude of oscillation.

LOUIS H. SCHALL, "Magnetron Current Control System," Patent No. 2,979,671

This patent relates to a magnetron current control system including a transformer with its secondary winding connecting the magnetron cathode to the field coil of the magnetron electromagnet. A rectifier couples the primary of the transformer to the field coil so that the magnetic field produced by the electromagnet is determined by the voltage applied to the primary and by the amount of current drawn by the magnetron cathode. When the magnetron draws excessive current the magnetic field changes to diminish the current.

SADIA S. GUTERMAN, "Intelligence Control System," Patent No. 2,980,803

This patent relates to a digital control circuit utilizing saturable cores carrying selectively operable windings to render ineffective (inhibit) the normal saturation polarity reversing action so that the signal-entering operation is nullified for the particular separating interval embraced by the selective inhibiting control.

JOSEPH J. OLIVER, LOUIS H. MORRISON, "Electrical Circuits for Pulse Generation," Patent No. 2,980,859

This patent relates to a pulsing circuit for magnetrons which uses a pedestal pulse to charge the stray capacitance of the magnetron to a voltage just below operating voltage and superimposed pulse to trigger the magnetron thereby providing fast rise times without mode skipping. Fast rise times are obtained when the normal pulse peak current would not raise the voltage of the stray capacity across the magnetron with the necessary speed. This method removes all voltages with associated radio frequency noise during the inter-pulse periods so that the receiver effectiveness is not impaired.

THOMAS A. O. GROSS, "Pulse Echo Systems," Patent No. 2,981,942

This patent relates to a circuit for producing a voltage proportional to the elapsed time between the transmission of a pulse and the reception of the echo of the pulse for use as a control voltage for controlling pulse duration, repetition rate, and bandwidth for maximum radar performance.

PAPERS & PUBLICATIONS

All papers which have been presented at scientific meetings and published in technical journals are being listed in this section of ELECTRONIC PROGRESS. In order to ensure completeness, authors are requested to advise the Secretary, Technical Publications Panel (Lexington X240) when papers are accepted for presentation and publication.

Papers Presented at Scientific Meetings

AIEE-IRE Conference on Electron Device Research, Troy, N.Y., June 21-23, 1961

M. CIFTAN, C. F. LUCK, C. G. SHAFER, H. STATZ, Research Division, "Some Properties of Optical Ruby Lasers." W. M. FEIST, Research Division, "Mono-Energetic Electrons from Photo-Cathodes." H. A. HAUS, R. C. HERGENROTHER, E. C. SCHEFFLER, B. M. TITLEBAUM, Microwave and Power Tube Division, "An Experimental Method for Measurement of S and π of Electron Guns." G. WADE, L. LESENSKY, Research Division, "Noise Analysis of Beam from Tunnel and Filter Cathodes." H. STATZ, C. F. LUCK, C. G. SHAFER, M. CIFTAN, Research Division, "Investigations on the Mode Patterns in Optical Masers." W. A. SMITH, M. ARNUM, Microwave and Power Tube Division, "A Mode Coupling Concept of Amplitron Interaction"

AIEE-IRE Solid State Device Research Conference, Stanford University, Calif., June 26-28, 1961

W. RINDNER, Research Division, "The Bonded NR Diode, A Current Controlled Negative-Resistance Diode." G. RUPPRECHT, R. O. BELL, R. A. PUCEL, Research Division, "Nonlinearity, Losses, and Figure of Merit in Cubic Strontium Titanate up to 36 kMc/sec."

American Ceramic Society Annual Meeting, Toronto, Canada, April 23-27, 1961

J. PAPPIS, S. L. BLUM, Research Division, "The Properties of Pyrolytic Graphite." S. L. BLUM, P. C. Li, Research Division, "Kinetics of Nickel Ferrite Formation."

American Ceramic Society, New England Section Meeting, Boston, Mass., May 24, 1961

S. L. BLUM, Research Division, "Advances of Pyrolitic Graphite in the Space Age."

American Physical Society Meeting, Washington, D.C., April 24-27, 1961

J. G. KELLEY, A. SMITH, F. E. STEIGERT, Equipment Division, "Bombardment of A^{40} with Mev O^{16} Ions." M. J. WEBER, L. RIMAI, L. NEURINGER, Research Division, "Nuclear Magnetic Resonance in Gallium Phosphide."

American Physical Society, New England Section Meeting, South Hadley, Mass., April 15, 1961

S. P. HEIMS, Equipment Division, "Derivation of Equilibrium Polarization of Nuclear Spins in a Solid."

American Physical Society Meeting, Mexico City, Mexico, June 22-24, 1961

E. J. ZDANUK, S. P. WOLSKY, Research Division, "Evaporated Titanium and Zirconium Films: Sorption Characteristics for Dry Air and Oxygen Below 10^{-4} Torr." S. P. WOLSKY, E. J. ZDANUK, Research Division, "The Sputtering of an Intermetallic Compound Semiconductor."

Conference on the Ultra-Purification of Semiconductor Materials, Boston, Mass., April 11-13, 1961

C. A. KLEIN, Research Division, "The Hall Effect as an Analytical Tool in Ultra-Pure Silicon and Germanium."

Conference on Components and Materials Used in Electronic Engineering, London, England, June 12-16, 1961

U. MILANO, E. SCHLOEMANN, Research Division, "Spin-Wave Instabilities in a Microwave Magnetic Field Applied Parallel to the DC Field." J. J. GREEN, J. H. SAUNDERS, E. SCHLOEMANN, Research Division, "Ferrite Materials for Microwave Applications at High Peak Power Levels."

Electrochemical Society Meeting, Indianapolis, Ind., April 30-May 4, 1961

W. RINDNER, J. M. LAVINE, Research Division, "Contact Etching." J. J. OBERLY, Research Division, "Electron-Diffraction Study of Crystalline Films on Germanium Surfaces." S. SHEFF, Semiconductor Division, "Electrolytic Slicing of Germanium." W. RINDNER, J. M. LAVINE, Research Division, "Preferential Plating and Etching, New Techniques for Microminiature and Other Devices." W. ERIKSEN, P. ROBINSON, H. VARTANIAN, Semiconductor Division, "Ambient Studies on the Switching Characteristics of the Avalanche Transistor."

Fifth Biennial Conference on Carbon, Penn State University, Pa., June 19-23, 1961

J. PAPPIS, L. HAGEN, R. DONADIO, Research Division, "The Thermal Conductivity of Pyrolytic Graphite." B. BOVARNICK, Research Division, "On the Establishment of Pyrolytic Graph-

ite Alloys." O. GUENTERT, S. CVIKEVICH, Research Division, "X-Ray Study of the Effects of Heat Treatment on Pyrolytic Graphites." C. A. KLEIN, Research Division, "Electronic Processes in Pyrolytic Graphites."

Fifth National Symposium on Global Communications, Chicago, Ill., May 22-24, 1961

C. F. CROCKER, Equipment Division, "A Technique for Converting Analog Voltages to Digital Codes at Sampling Rates Above Five Million Samples per Second with Accuracies of Seven Bits." G. HARMON, Equipment Division, "Radio Wave Propagation Through the Earth's Deep Rock Strata—A New Medium of Communication."

IRE National Convention on Military Electronics, Washington, D.C., June 26-28, 1961

F. W. NESLINE, Missile and Space Division, "Polynomial Filtering of Signals." S. AMEEN, R. F. PLUMRIDGE, Microwave and Power Tube Division, "Characteristics of a Backward Wave Oscillator Employing an External Feedback Circuit." H. C. KREIDE, J. V. POPOLO, Missile and Space Division, "A Target Angle Computation Method for Multibeam Radars." D. A. ALLEN, C. E. DANTAS, H. C. KREIDE, Missile and Space Division, "Pulse-to-Pulse Target Correlation with Range-Only Data." G. WADE, Research Division, "Survey of Modern Low-Noise Amplifiers." A. P. SCHMID, Research Division, "Some Circuit Considerations for Application of the Avalanche Injection Diode." J. D. HARMER, W. S. O'HARE, Missile and Space Division, "Some Advances in CW Radar Techniques." C. C. ABT, Missile and Space Division, "AUDIT, An Automatic Unattended Detection Inspection Transmitter for the Monitoring of the Nuclear Test Ban."

IRE National Aerospace Electronics Conference, Dayton, Ohio, May 8-10, 1961

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L. L. CLAMPITT, Microwave and Power Tube Division, "High Power Amplitron Chains."

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